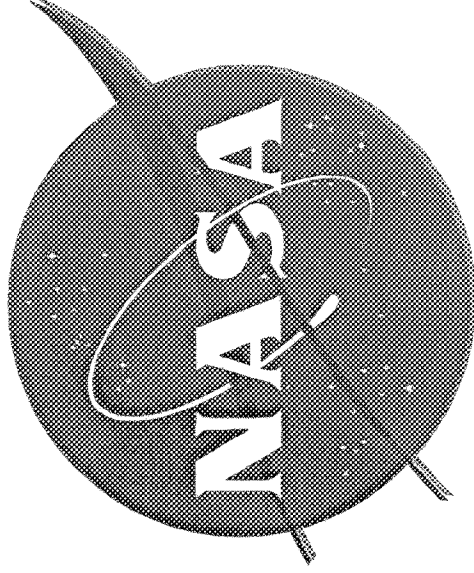


HIGH TEMPERATURE MATERIALS NEEDS IN NASA'S ADVANCED SPACE PROPULSION PROGRAMS, Andrew J. Eckel, NASA Glenn Research Center, Cleveland, OH 44135

In recent years, NASA has embarked on several new and exciting efforts in the exploration and use of space. The successful accomplishment of many planned missions and projects is dependent upon the development and deployment of previously unproven propulsion systems. Key to many of the propulsion systems is the use of emergent materials systems, particularly high temperature structural composites.

A review of the general missions and benefits of utilizing high temperature materials will be presented. The design parameters and operating conditions will be presented for both specific missions/vehicles and classes of components. Key technical challenges and opportunities are identified along with suggested paths for addressing them.

High Temperature Materials Needs in NASA's Advanced Space Transportation Programs



Andrew J. Eckel

**Glenn Research Center
Cleveland, Ohio, USA**

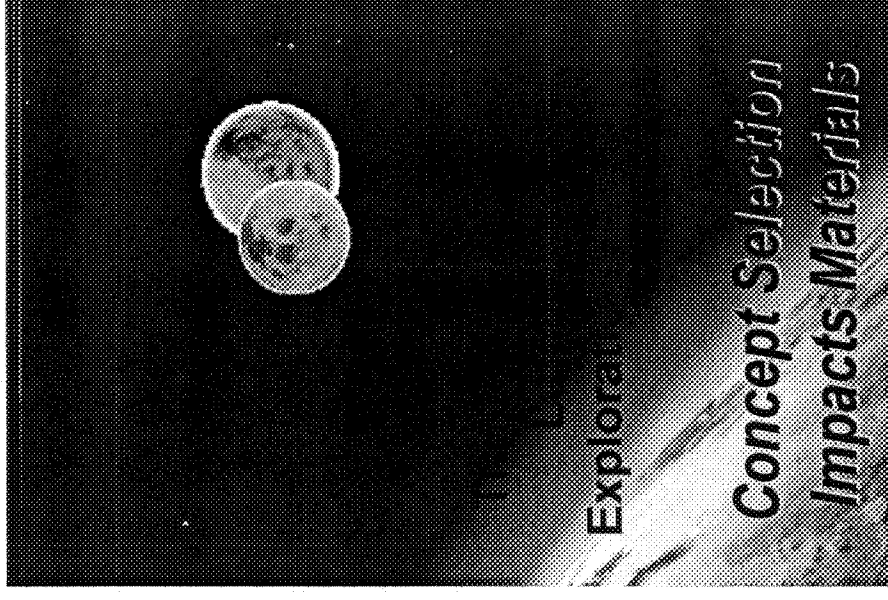
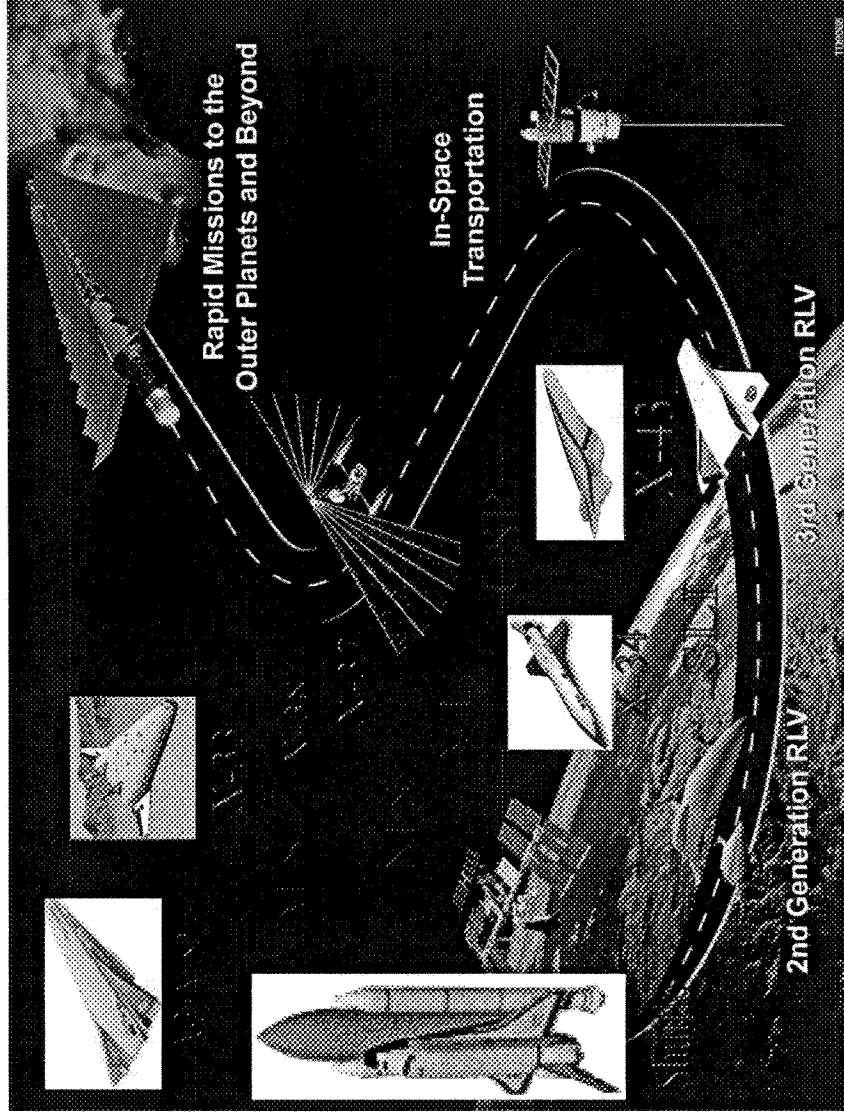
David E. Glass

**Langley Research Center
Hampton, VA USA**

Outline

- ◆ **Introduction**
- ◆ **Airframe**
 - Hot & Integrated Structures
 - Tanks
 - TPS
- ◆ **Propulsion**
 - Rotating Components and Seals
 - Flowpath Components
- ◆ **Concluding Remarks**

Advanced Space Transportation Program(s) - ASTP



Materials enable NASA missions!

Rockets

◆ Don't like the atmosphere

- Accelerate only
- Get out quick
- Tend toward vertical launch
- Low ISP

◆ Drag

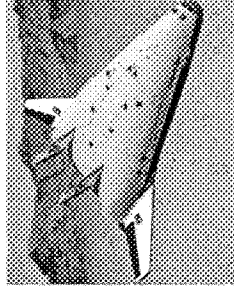
- High drag not a problem on ascent, desirable on descent for deceleration
- Blunt leading edges

◆ Weight critical

- Mass fraction ~ 10% of GTOW
- Requirement to be weight sensitive

◆ Engine in back

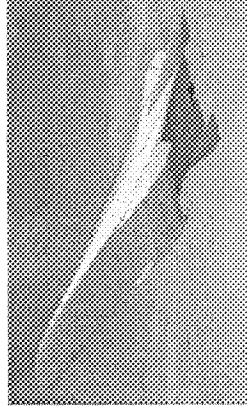
- Weight drives components to be clustered near engine
- Tail heavy
- Hard to get forward cg
- Highly compressive loaded structure



Airbreathers

◆ Like the atmosphere

- Accelerate and cruise in atmosphere
- Tend toward horizontal launch
- High ISP



◆ Drag

- Optimize for low drag
- Thin, slender body, low thickness/chord

◆ Volume critical

- Mass fraction ~ 30% of GTOW
- Requirement to be volume sensitive, volume drives drag

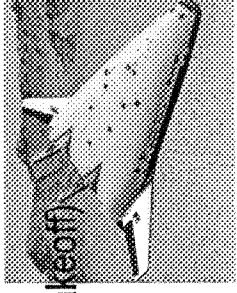
◆ Engine in mid-body

- Stability easier
- Easier to control cg
- Can split LOX for cg control

Rockets vs. Airbreathers Effect on Airframe

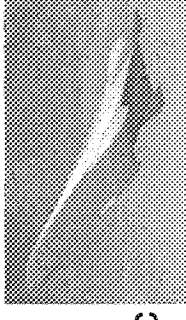
Rockets

- ◆ **TPS**
 - Driven by descent
 - Low heat load due to short ascent
- ◆ **Leading edges**
 - Blunt due to desire for descent drag
 - Low heat flux
- ◆ **Tanks**
 - Cylindrical since weight sensitive and volume insensitive
- ◆ **Structure**
 - Lightly loaded wings
 - Propulsion and airframe not highly integrated
- ◆ **Landing gear**
 - Sized for empty descent (vertical takeoff)
 - Lightly loaded
 - Light weight



Airbreathers

- ◆ **TPS**
 - Driven by ascent
 - High heat load due to long ascent time
- ◆ **Leading edges**
 - Sharp due to low drag, low t/c
 - High heat flux
- ◆ **Tanks**
 - Conformal since volume and drag critical
- ◆ **Structure**
 - Highly loaded wings (some air breathers)
 - Hot wings and control surfaces due to thin cross sections and high heat flux/load
 - Propulsion and airframe highly integrated
- ◆ **Landing gear**
 - Sized for fully loaded ascent
 - Highly loaded
 - Significant weight



Key Drivers for Utilizing Higher Temperature Capable Advanced Materials

- **Weight:**
 - ▶ High Thrust-to-Weight for Launch Vehicles
 - ▶ Lower Propulsion System Mass for Satellite and Planetary Missions
- **Enabling:** High Temperature Capability and/or Oxidation Resistance Enabling for Many Propulsion Concepts
- **Performance:** Increased operational margin -- translates to enhanced range, life and/or system payload (e.g., E-T-O propulsion systems, satellites, deep space probes)
- **Simplicity:** Higher temperature capability may reduce or eliminate coolant system requirements (e.g., on re-entry)
- **Cost:** Reduced System Operational Costs (e.g., less inspections, rebuilds)

ASTP High Temperature Materials Needs

What are we working today?

- ◆ **Airframe**

- Hot Structures/Control Surfaces
- Tanks
- TPS

- ◆ **Propulsion**

- Rotating Components and Seals
- Flowpath Components

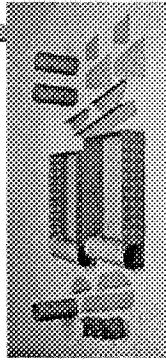
CMC Control Surfaces

♦ Objective

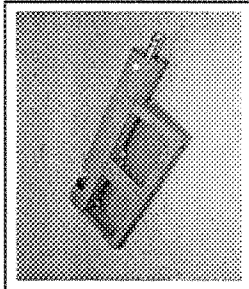
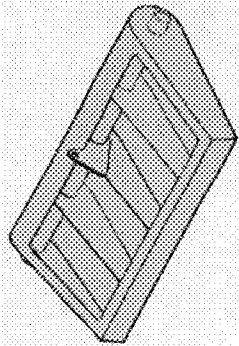
- Dev elop hot structure control surfaces with multi-use mission life that are reliable, durable, and lightweight.

♦ Materials

- Carbon/Carbon (C/C)
- Carbon/Silicon Carbide (C/SiC)
- Oxidation protection systems
- C/SiC joining technology
- Comingled SiC and C fibers to reduce microcracks
- Tow-spreading to increase performance



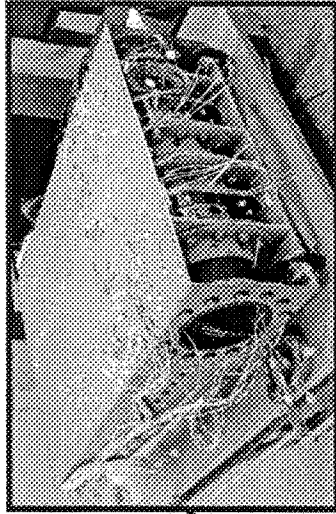
♦ Design and Analysis



- CMC body flap design (design tools development)
- Life/oxidation modeling development and stressed oxidation tests

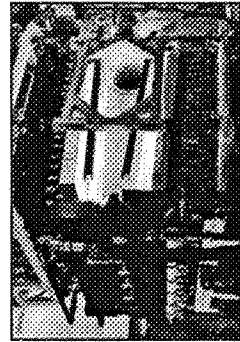
♦ Advanced Fabrication

- Advanced fabrication demonstration, integrally fabricated flaperon (WPAFB-AFRL)

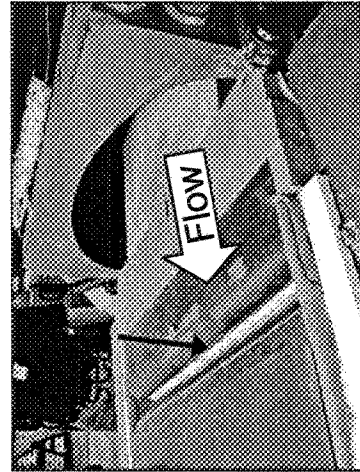


♦ Validation and Testing

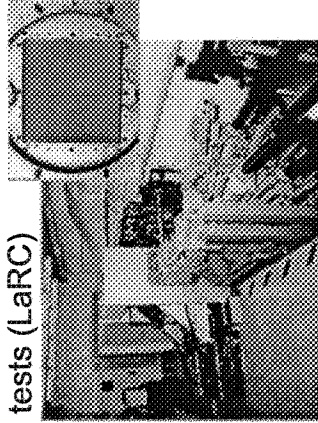
- Body flap subcomponent test (DFRC)



- CMC control surface seal validation arcjet test (GRC/ARC/JSC/LaRC)

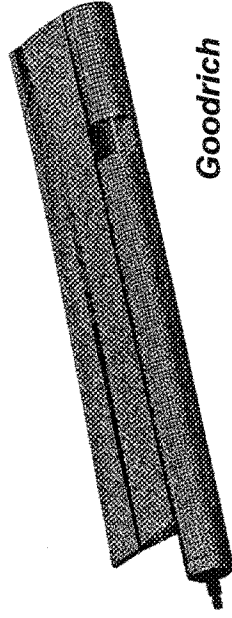


- Vibration and vibroacoustic tests (LaRC)



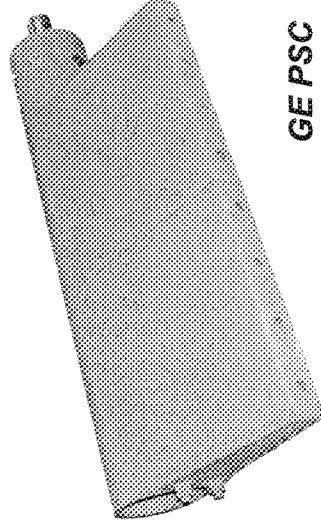
C/SiC Body Flap

- ◆ Half-scale X-37 body flap was fabricated and tested at NASA Dryden under combined heating and loading to 2050°F and 100% design limit load (report available)
- ◆ Acoustic / vibration testing at NASA Langley upcoming
- ◆ Design methodology task performed by SRI (report available)
- ◆ Follow-on tasks to enhance control surface performance
 - Oxidation resistance
 - Fastener improvement
 - Failure testing
 - Integrated fabrication



Goodrich

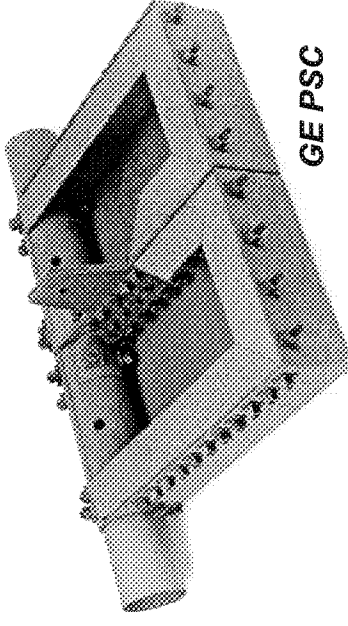
C/SiC Flaperon
Advanced Fabrication Demonstration
(Integrated Fabrication)



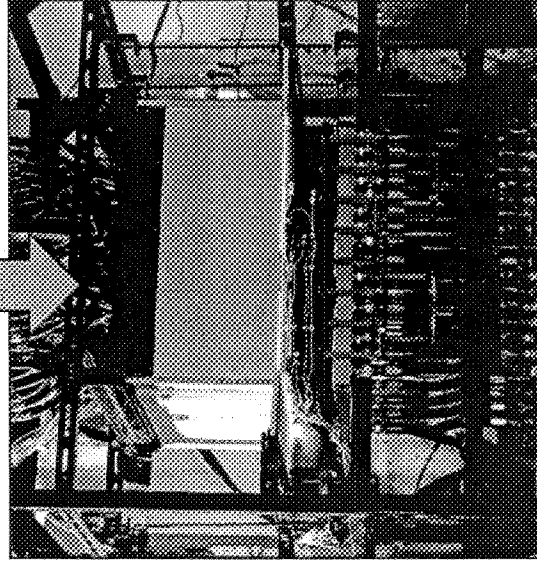
GE PSC

X-37 C/SiC Flaperon
Subcomponent Utilizes
NGLT Lessons Learned

Half-Scale X-37 Body Flap

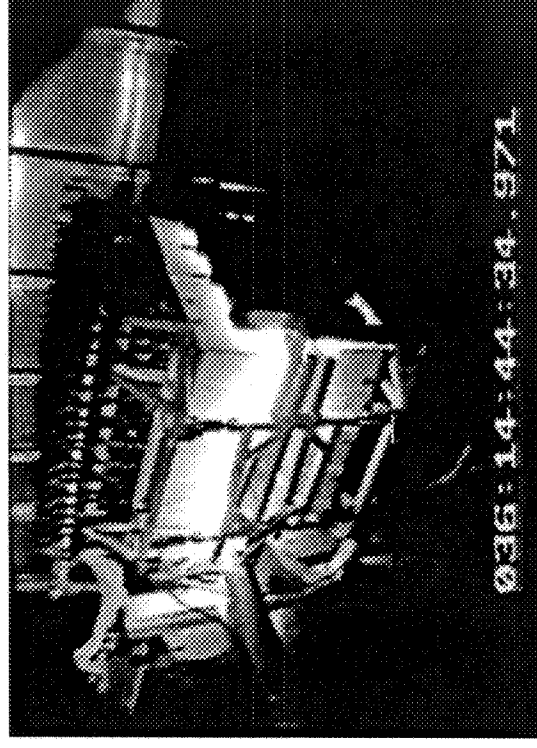
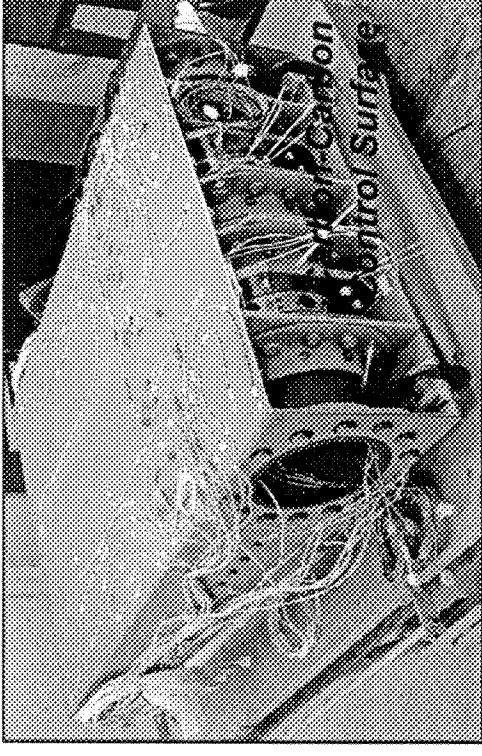


GE PSC



Carbon-Carbon Control Surface

- ◆ **CMC Control Surface Development Thermostructural Testing (DFRC)**
- ◆ **Accomplishments**
 - Developed test setup and test techniques required to test a CMC bodyflap through the thermal-structural testing of the C/C control surface
 - Performed combined thermal and mechanical testing of a hot structure test component
 - Demonstrated the ability to measure strains on a hot structure at 1650°F using fiber optic strain sensors



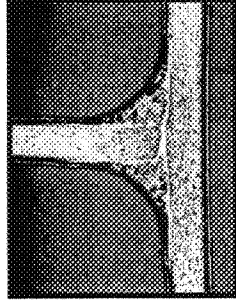
Metallic Materials for Hot Structures

◆ Objective

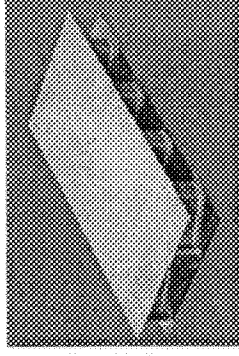
- Develop metallic material systems and processing/fabrication technology for production of reliable, durable, lightweight hot structure and TPS components

◆ Fabrication

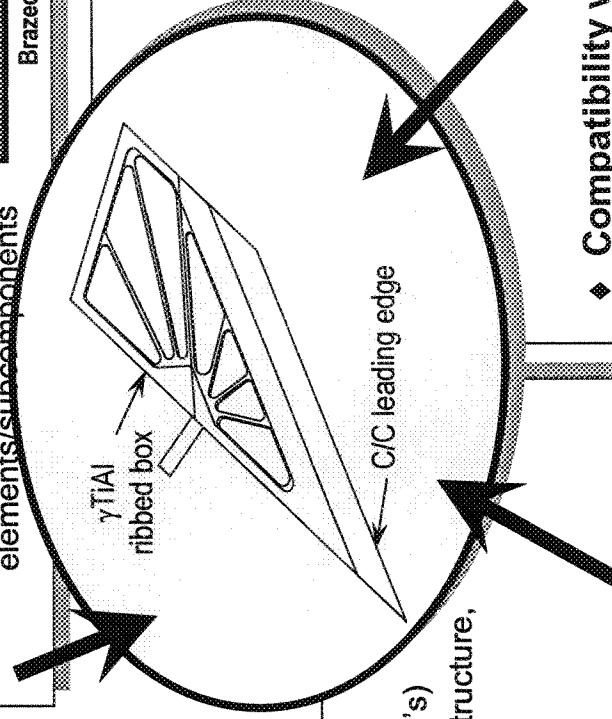
- Fabrication of appropriate shapes and product forms
- Joining
- Fabrication of structural elements/subcomponents



Brazed Joint



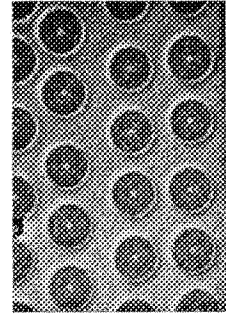
γ TiAl Truss Core Panel



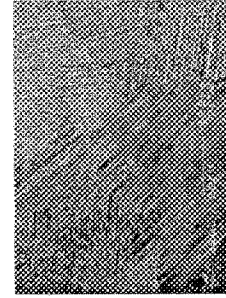
◆ Materials Development

(γ TiAl, adv. Ni and Fe alloys, MMC's)

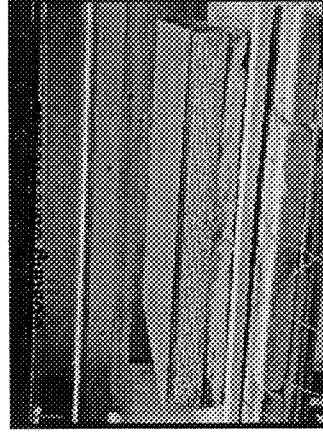
- Correlate and optimize microstructure, properties, and processing
- MMC fiber-matrix compatibility (chemical, mechanical)
- MMC laminate fabrication



SiC/Ti MMC



γ TiAl



◆ Compatibility with Service Environments

- Assess environmental service limits of candidate materials
- Develop coatings for environmental protection and thermal control
- Assess impact resistance and durability of candidate materials and structural elements

High Temperature PMC's

♦ Objective

- Develop non-autoclave processable polymeric resins, composites, and adhesives suitable for use in airframe components at temperatures from -150°F to 700°F

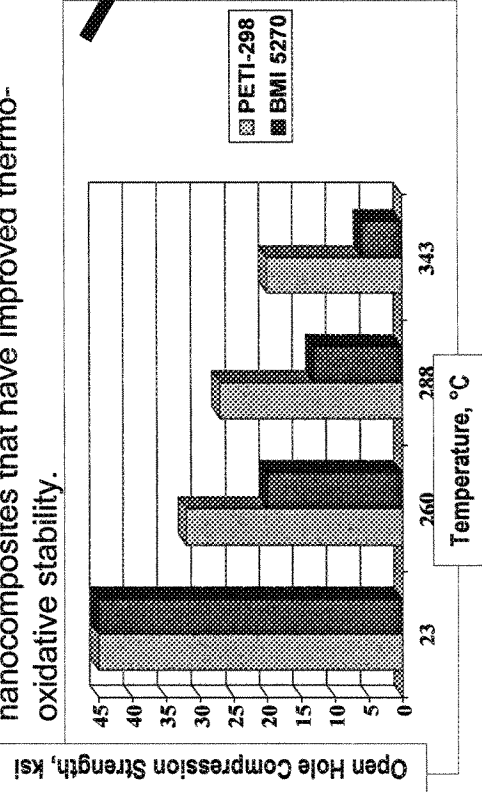
♦ Determine failure modes that affect durability of advanced high temperature polymeric materials

- Produce adequate amounts of materials for important properties of the high temperature polymeric materials.
- Understand the effects of complex loads and environments on materials durability and life.



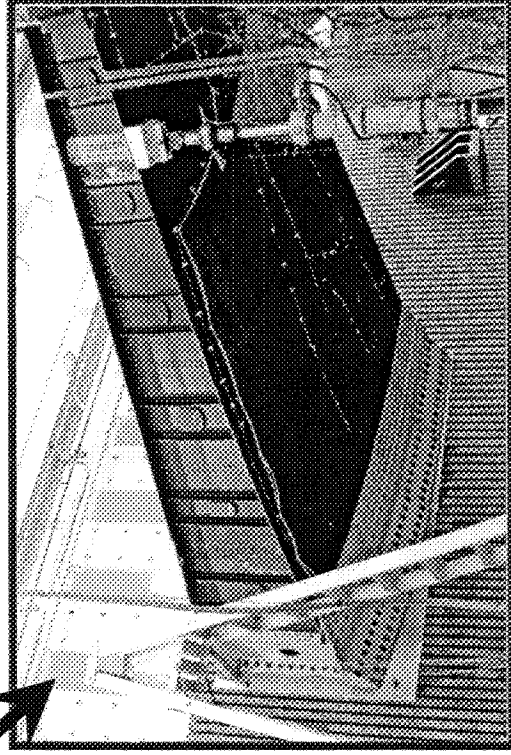
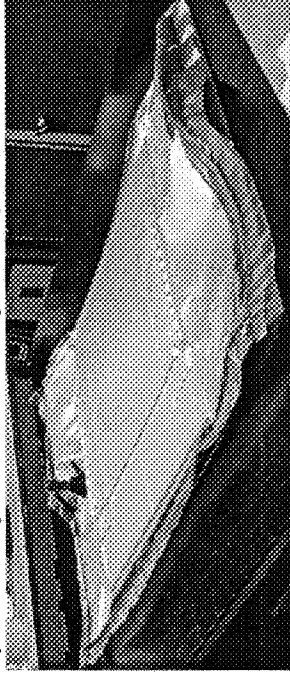
♦ Fully characterize properties of high temperature resistant structural materials

- Develop high temperature resistant / clay nanocomposites that have improved thermo-oxidative stability.



♦ Develop and demonstrate high temperature resistant structural materials

- Develop materials with proper combination of high and low temperature mechanical properties.
- Optimize processability and properties



Photographed structure not developed as part of NGLT¹²

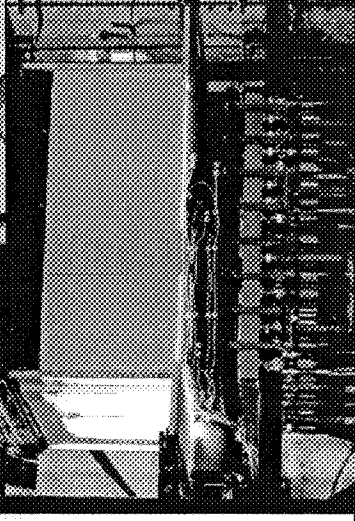
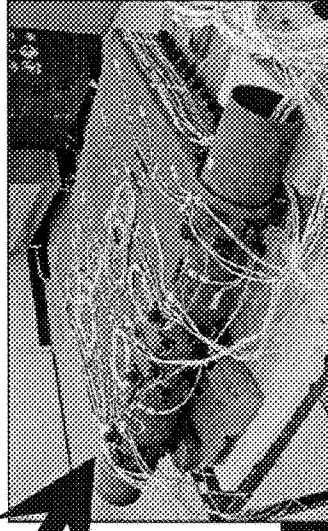
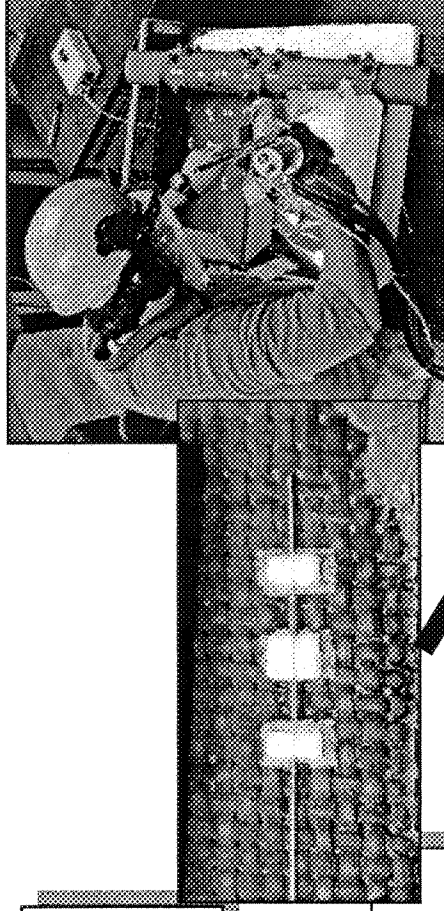
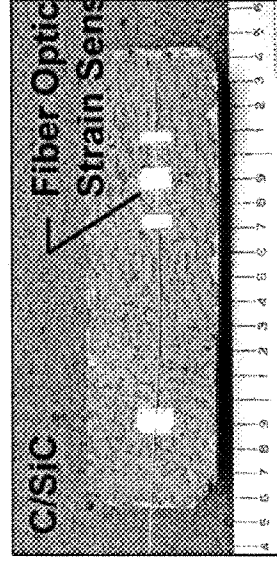
Fiber Optic Sensors

◆ Objective

- Develop high temperature and multi-parameter (cryogenic) fiber optic sensors

◆ High temperature sensors for use up to 3000°F

- Develop techniques to bond sapphire optical fiber to CMC materials for use at 2500°F and 3000°F
- Evaluate the performance of silica and sapphire based FO sensors through CMC coupon testing to maximum use temperature

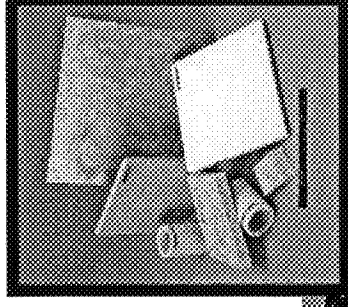
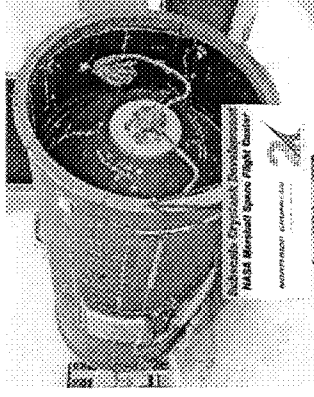


1850°F Test of Fiber Optic Strain Sensor on C/SiC Hot Structure

Tanks

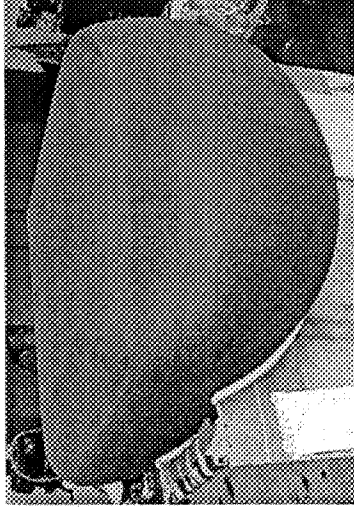
◆ Hot & Integrated Structures

- CMC Control Surfaces
- Metallic Materials for Hot Structures
- High Temperature PMC's
- Fiber Optic Sensors



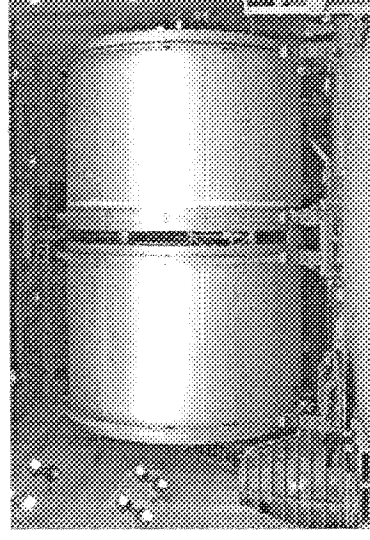
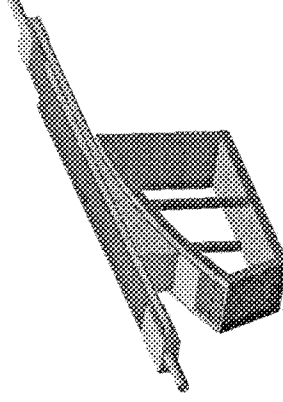
◆ Tanks

- Composite Tanks
- Metallic Tanks
- Cryoinsulation



◆ TPS

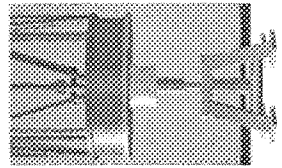
- Acreage
 - CMC Acreage TPS
 - Metallic TPS
 - Ablators
 - Blankets
 - Tiles
- Leading Edges
 - 3000°F Passive Leading Edges
 - 3600°F Passive Leading Edges
 - Heat-Pipe-Cooled Leading Edges
- Control Surface Seals



Composite Tanks

♦ Materials

- Validated life prediction tools including permeation
- Develop - 450°F to 550°F non-autoclave processable composites and adhesives

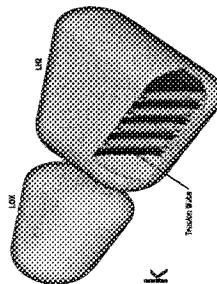


- Cryo-biaxial life cycling of sandwich panels with in-situ permeation

♦ Objective

- Develop the technology required to design and fabricate full scale, reusable, composite cryogenic tanks

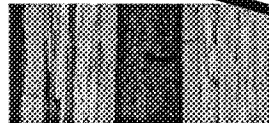
♦ Design and Analysis



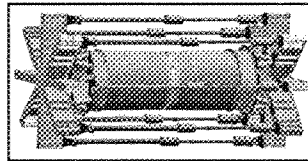
- Conformal tank design trades

- Web joint structural member scaled to reference vehicle

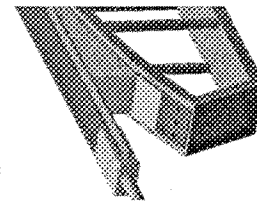
- Composite fracture control & residual life tools



♦ Verification

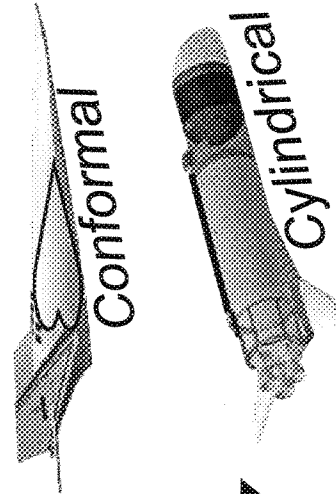


- > 40 LH2 cryo-structural cycles on NG subscale tank



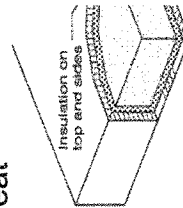
- Complete cryo testing of Y-joints

- Curved panel test data
- Cryo-structural testing of conformal tank web joint

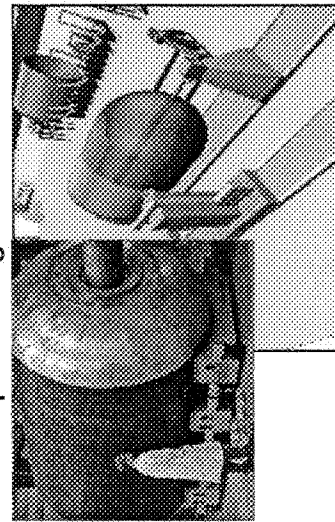


♦ Fabrication

- Heat-pipe heat blanket for composite repair

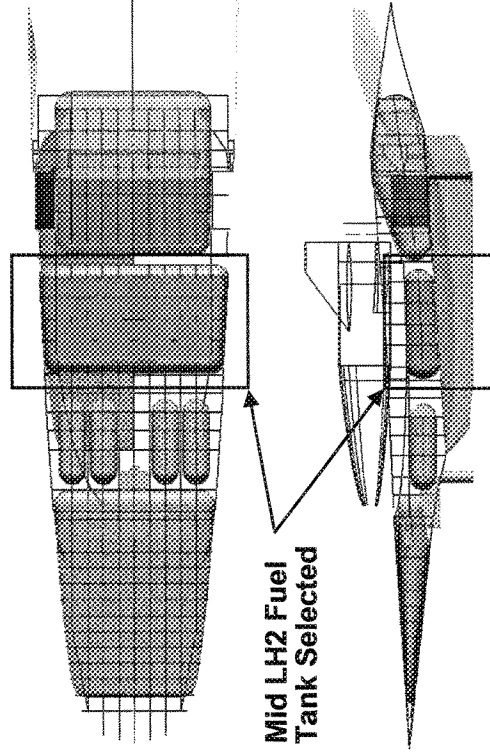
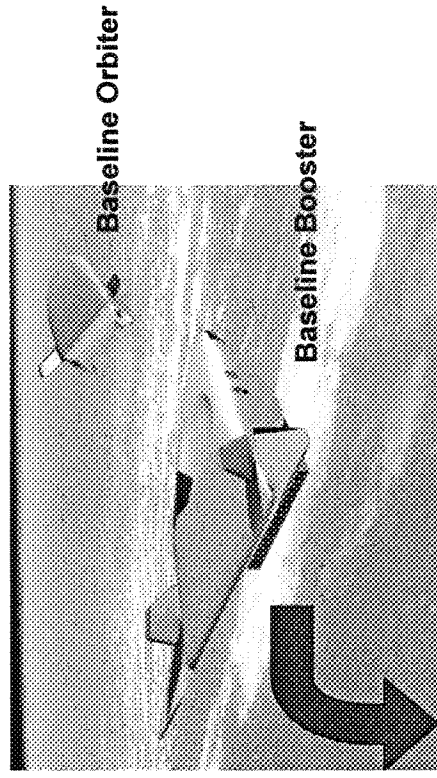


- Non-autoclave, tow placement fabrication of a 10.5 ft diameter half tank, including post test coupon testing and NDE.



Conformal Tank Joint Concepts – 4 Selected

- Conformal Tanks Require Internal Members for Shape Retention



3rd Gen RLV Booster - Mach 8



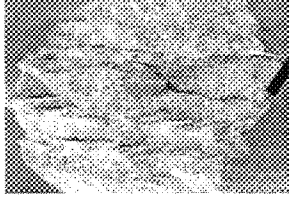
Candidate Shape
Retention Joint
Attachments to
Composite
Sandwich Tank

2 Linear Web Attach Concepts	
1 – Linear Flat Vee	2 – Linear Box Beam
2 Discrete Truss Attach Concepts	
3 – Discrete Disk	4 – Discrete Ashtray

Metallic Tanks

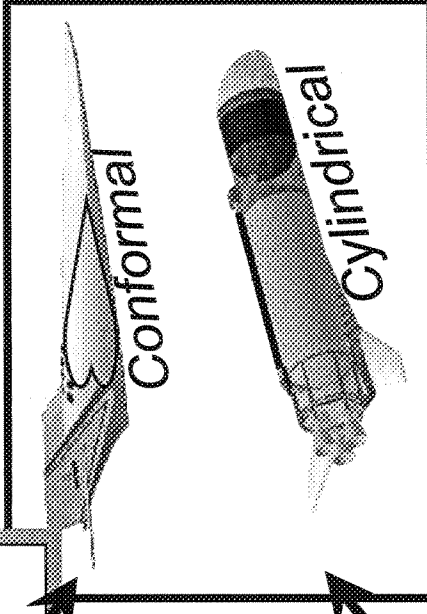
♦ Materials

- Understanding Al alloy delaminations
 - What induces delams?
 - Design around them?
- Alternative alloys
 - System payoffs?



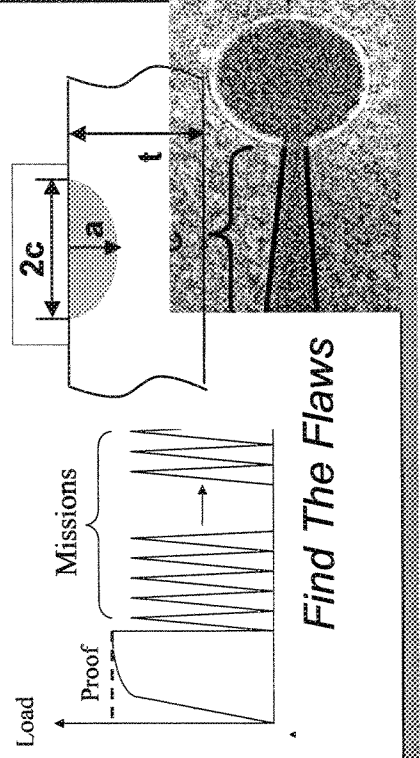
♦ Objective

- Develop the technology required to design and fabricate full scale, reusable, metallic cryogenic tanks



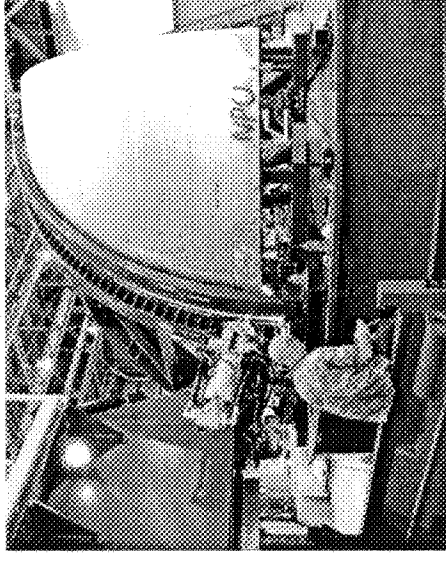
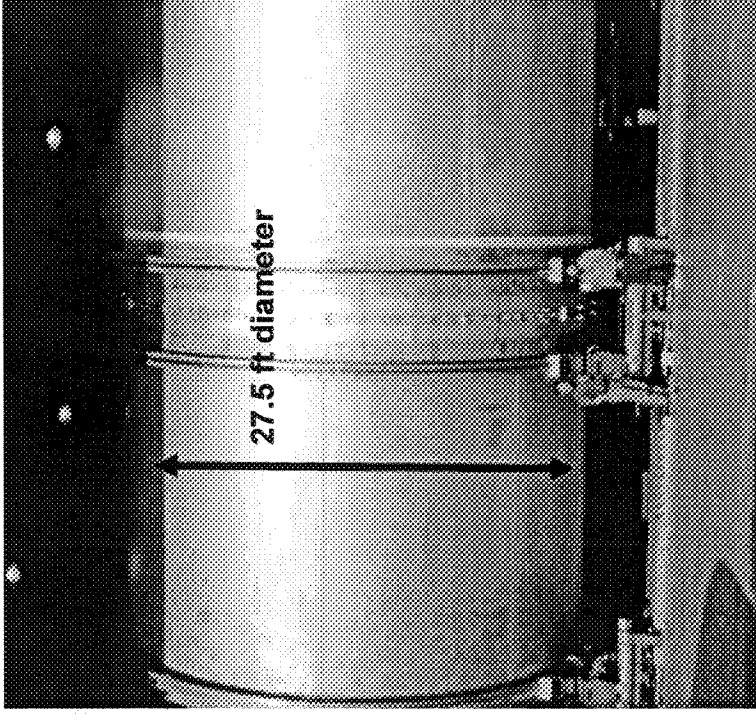
♦ Design and Analysis

- Maturing tank life verification strategies
 - NDE based statistical approach?
 - Proof test method?



Self Reacting-Friction Stir Welding

- ◆ Successful completion of full-scale circumferential FSW
- ◆ Successful SR-FSW of three gore dome welds
 - Final confidence panels welded – strength properties box shifted to the “colder side”, pin tool RPM and travel speed must be slightly reduced
- ◆ Self-Reacting FSW is an enabling technology for (1) Reusability (near zero defect joints) and (2) Low Cost (self-reacting eliminates much tooling costs)



♦ Objective

- Develop a reusable high use temperature (450°F) cryoinsulation that can be applied to complex structures by spray techniques or secondary bonding.

♦ Reusable polyimide foam insulation which eliminates cryopumping

- Develop a process cycle which allows greater than 80% closed cells for a polyimide foam having a density of 2.0 pcf to 4.5 pcf.
- Develop a process cycle which allows foam filled honeycomb to be fabricated without causing degradation to organic honeycomb core.
- Develop a process to fabricate curved polyimide foam and foam filled honeycomb structures.



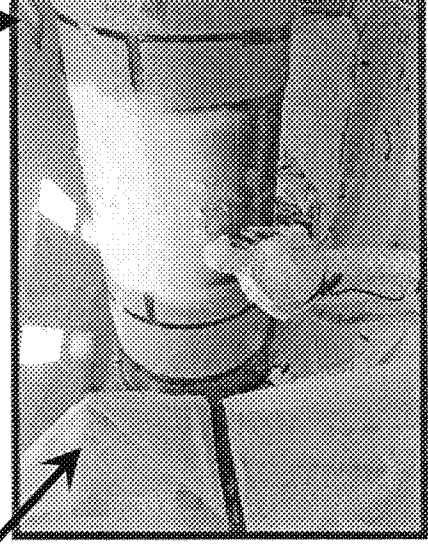
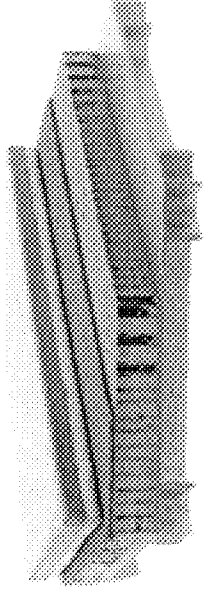
♦ Develop Spray on Polyimide Foam Technique

- Develop a spray on polyimide foam process cycle which allows application to complex structure.
- Optimize process cycle to produce polyimide foam with more than 80% closed cells having a density of 2.0 pcf to 4.5 pcf.
- Fully characterize physical properties of polyimide foams produced by spray on process.

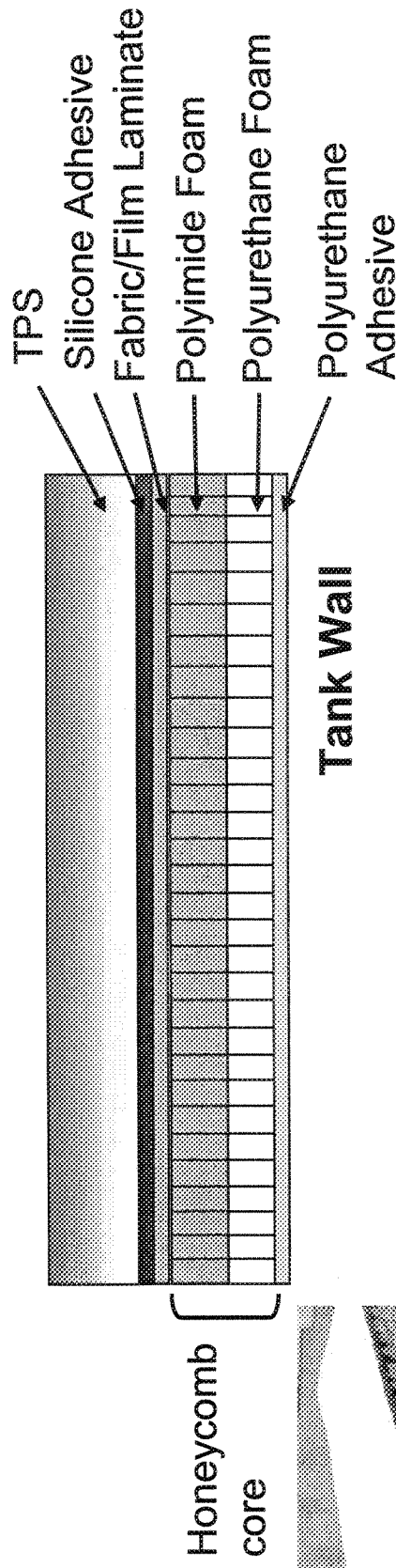
QuickTime™ and a
GIF decompressor
are needed to see this picture.

♦ Optimize the secondary bonding procedure and characterizing the reusable polyimide foam

- Develop a process to form strong adhesive bonds between the foam and structure without damaging either.



Foam Filled Honeycomb Cryo-Insulation



Standoff Panel

Bonded Panel

Component	Material	Function
Foam	PDL-1034 Polyurethane Foam (adjacent to tank wall)	Cryogenic insulation
	TEEK Polyimide Foam (adjacent to TPS)	Contribute to structure thermal protection
		Cryogenic insulation
		Contribute to structure thermal protection
		Provide higher temperature capability/minimize TPS weight
Honeycomb	Nomex Aramid Fiber/Phenolic Resin (3/8-in cell)	Provide additional strength to the foam
Fabric/Film Laminate	BMI 2550 Supported Film Adhesive	Provide further strain compatibility with the metallic cryotank
		Provide uniform surface for TPS bonding

Thermal Protection Systems

◆ Hot & Integrated Structures

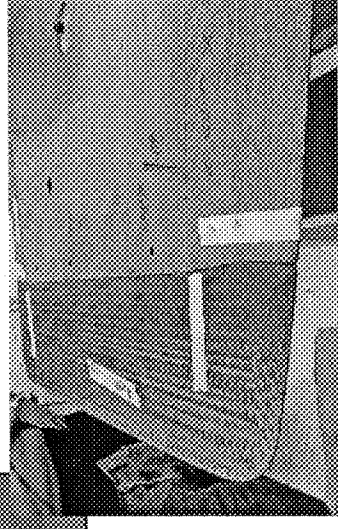
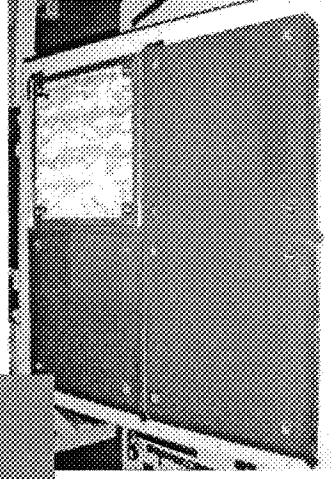
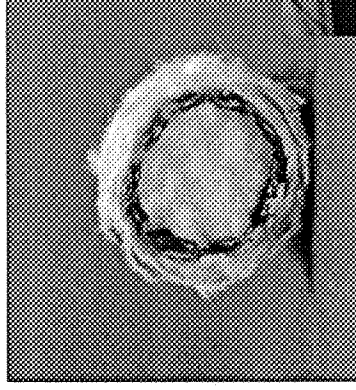
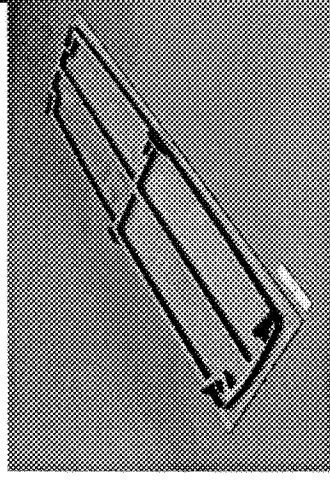
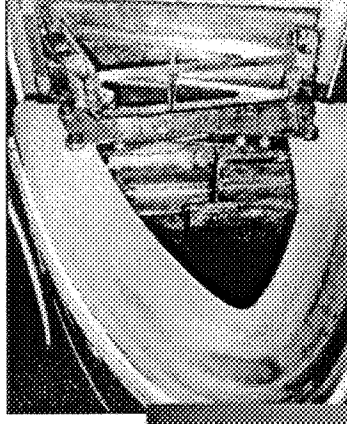
- CMC Control Surfaces
- Metallic Materials for Hot Structures
- High Temperature PMC's
- Fiber Optic Sensors

◆ Tanks

- Composite Tanks
- Metallic Tanks
- Cryoinsulation

◆ TPS

- Acreage
 - CMC Acreage TPS
 - Metallic TPS
 - Ablators
 - Blankets
 - Tiles
- Leading Edges
 - 3000°F Passive Leading Edges
 - 3600°F Passive Leading Edges
 - Heat-Pipe-Cooled Leading Edges
 - Actively Cooled Leading Edges
- Control Surface Seals

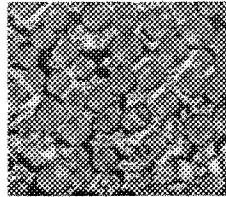


◆ Objective

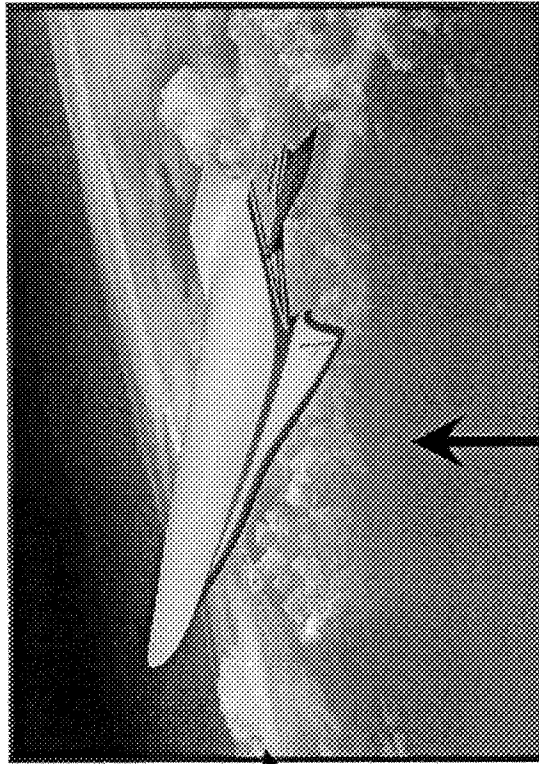
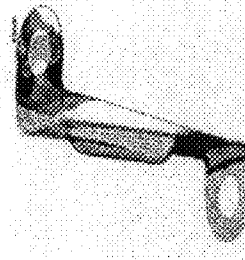
- Develop and demonstrate a ceramic matrix composite (CMC) TPS for multi-use on RLV's

◆ Analysis

- **Loads and material properties:** Identify design loads and requirements, assemble candidate material thermal/structural properties

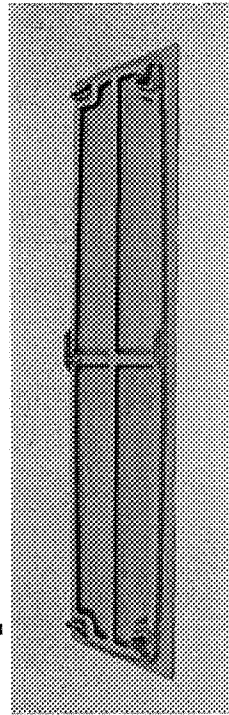
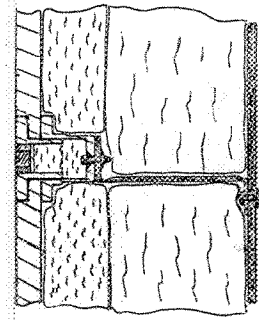


- **Thermal/structural sizing of candidate concepts:** Preliminary mass estimates, investigate critical design issues



◆ Concept development

- **Identify candidate concepts:** Attachments, seals, panel size and configuration, insulation packaging



- **Fabricate prototypes of promising concepts/constituents:** Investigate attachment concepts, seal configuration, panel removal, etc.

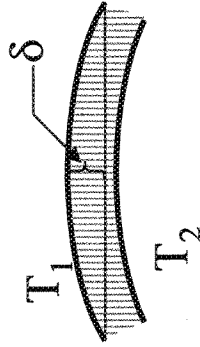
Metallic TPS

◆ Objective

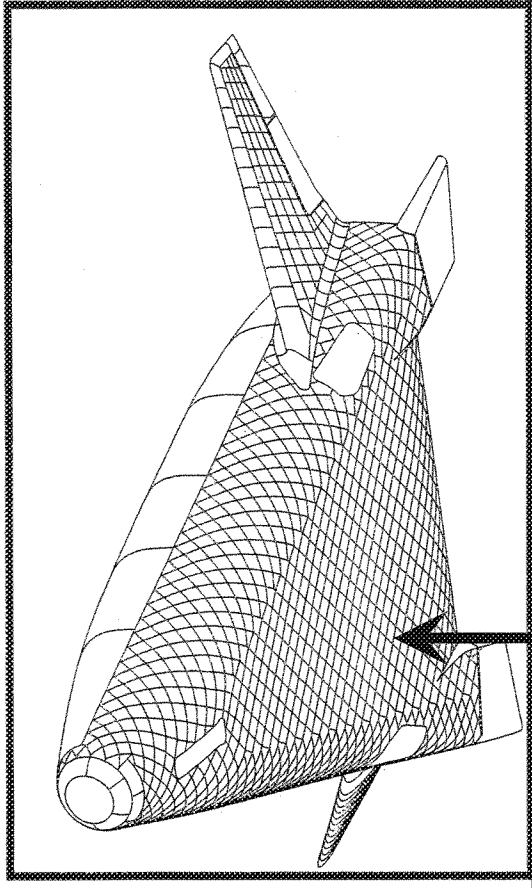
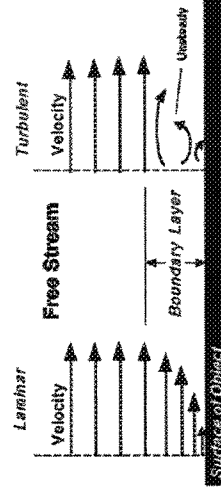
- Develop and demonstrate a metallic TPS for multi-use on RLV's

◆ Effects of Thermal Bowing

- Analytical predictions
Entry thermal bowing history

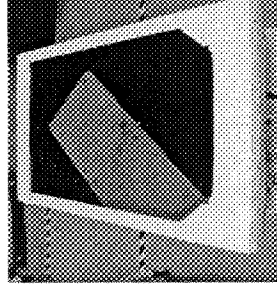
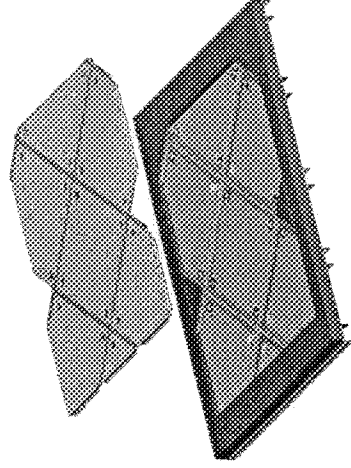


- Wind tunnel verification
Effect of bowed shapes on boundary layer transition



◆ Verification

- Radiant pressure tests
Combined elevated temperatures and pressure

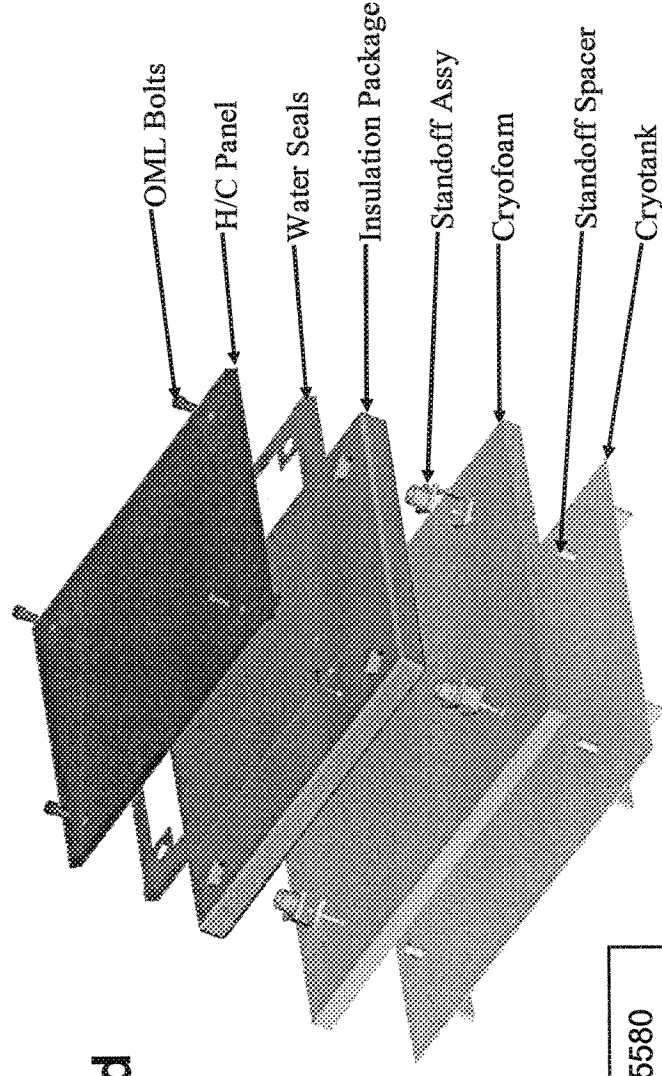


- 8 Ft HTT tests
Combined elevated temperatures, acoustics, pressure, and hot gas flow

Metallic Thermal Protection Systems

- ◆ Improved durability to micro-meteoroid and orbital debris (MMOD) and foreign object damage (FOD) compared to ceramic systems
- ◆ Does not require chemical waterproofing or re-waterproofing
- ◆ Highly modular design with mechanical attachment

- ◆ Reduced maintenance and repair turnaround
- ◆ Capable of flight through most weather conditions

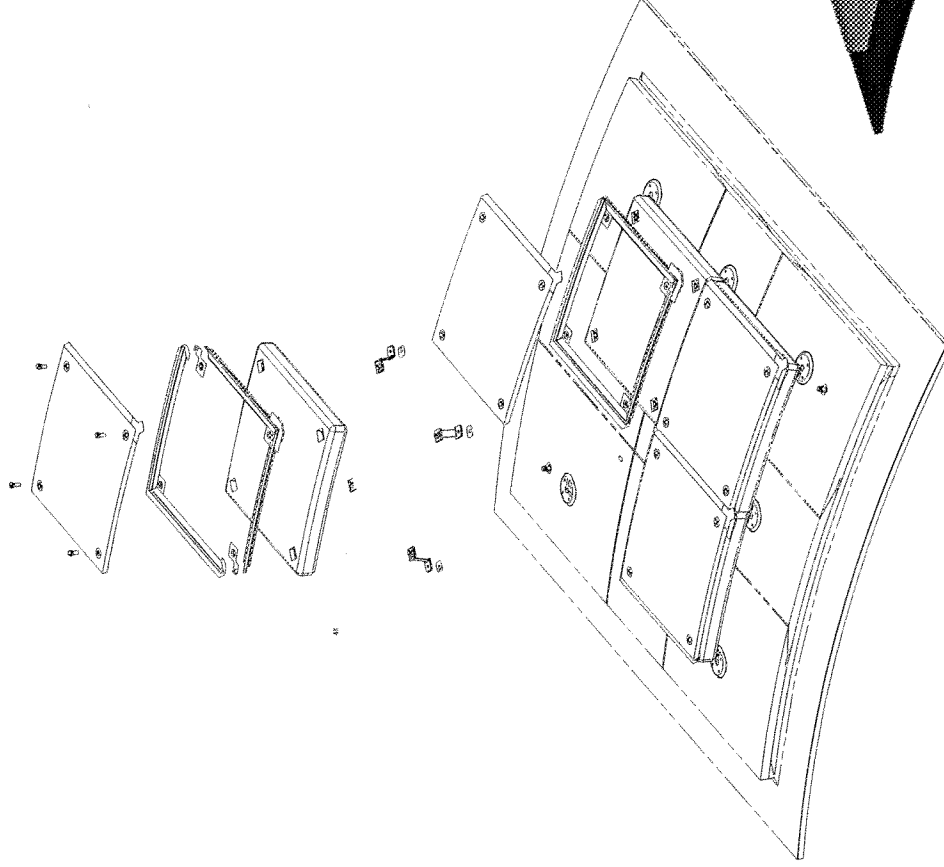


POC: Marty Agrella, Oceaneering, (281) 228-5580

Curved MTPS

◆ Primary Components

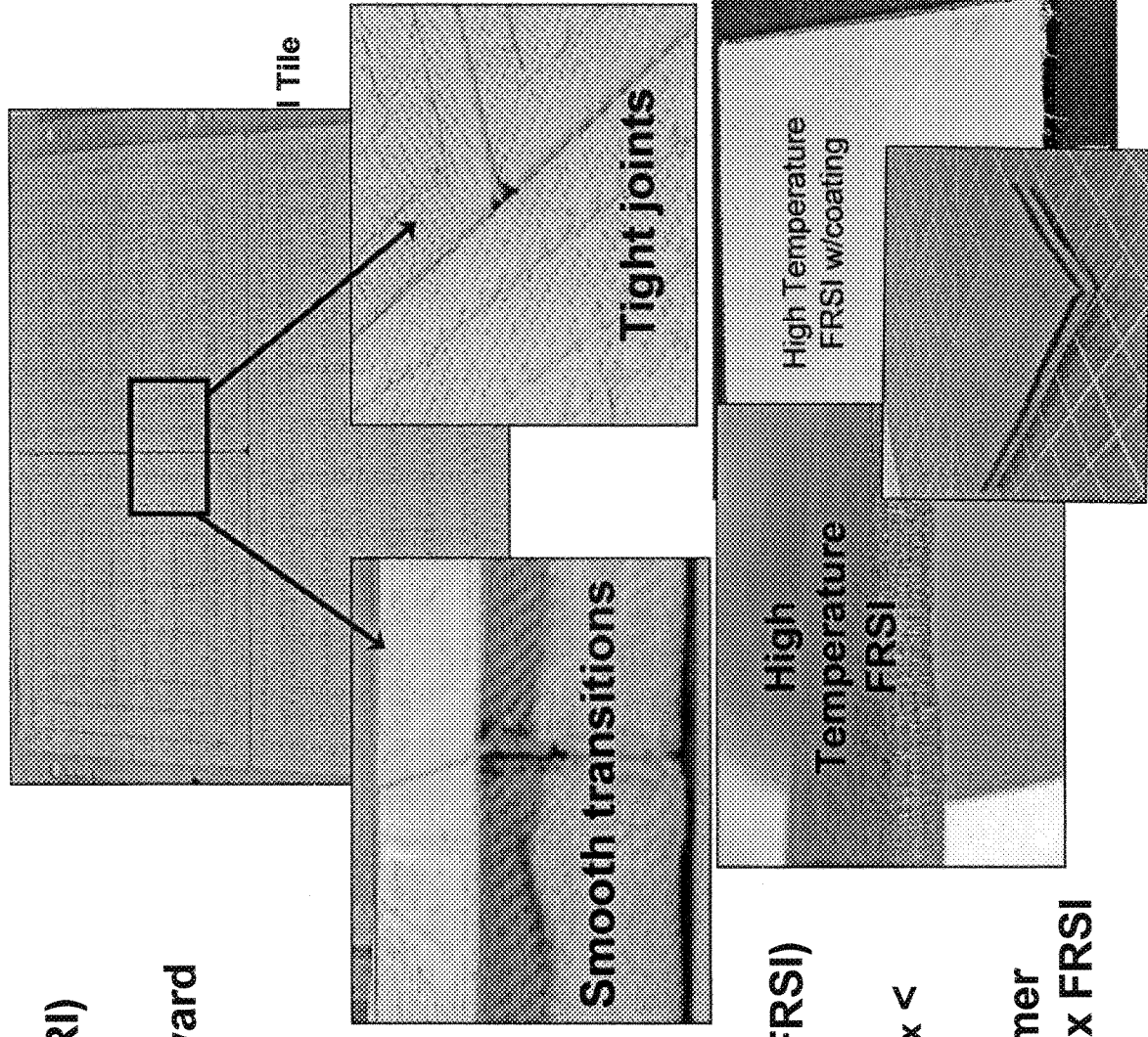
- Metallic OML Panel
- Perimeter Water Seals
- OML Fasteners
- Standoffs to IML
- Insulation Packages



Durable Acreage TPS Technologies

Conformal Reusable Insulation (CRI)

- Durable, Low Cost Acreage TPS applicable to windward and leeward surfaces where $T_{\max} < 2400^{\circ}\text{F}$
- New class of improved ceramic TPS for windward surfaces based on heritage flexible blanket and CMC technology

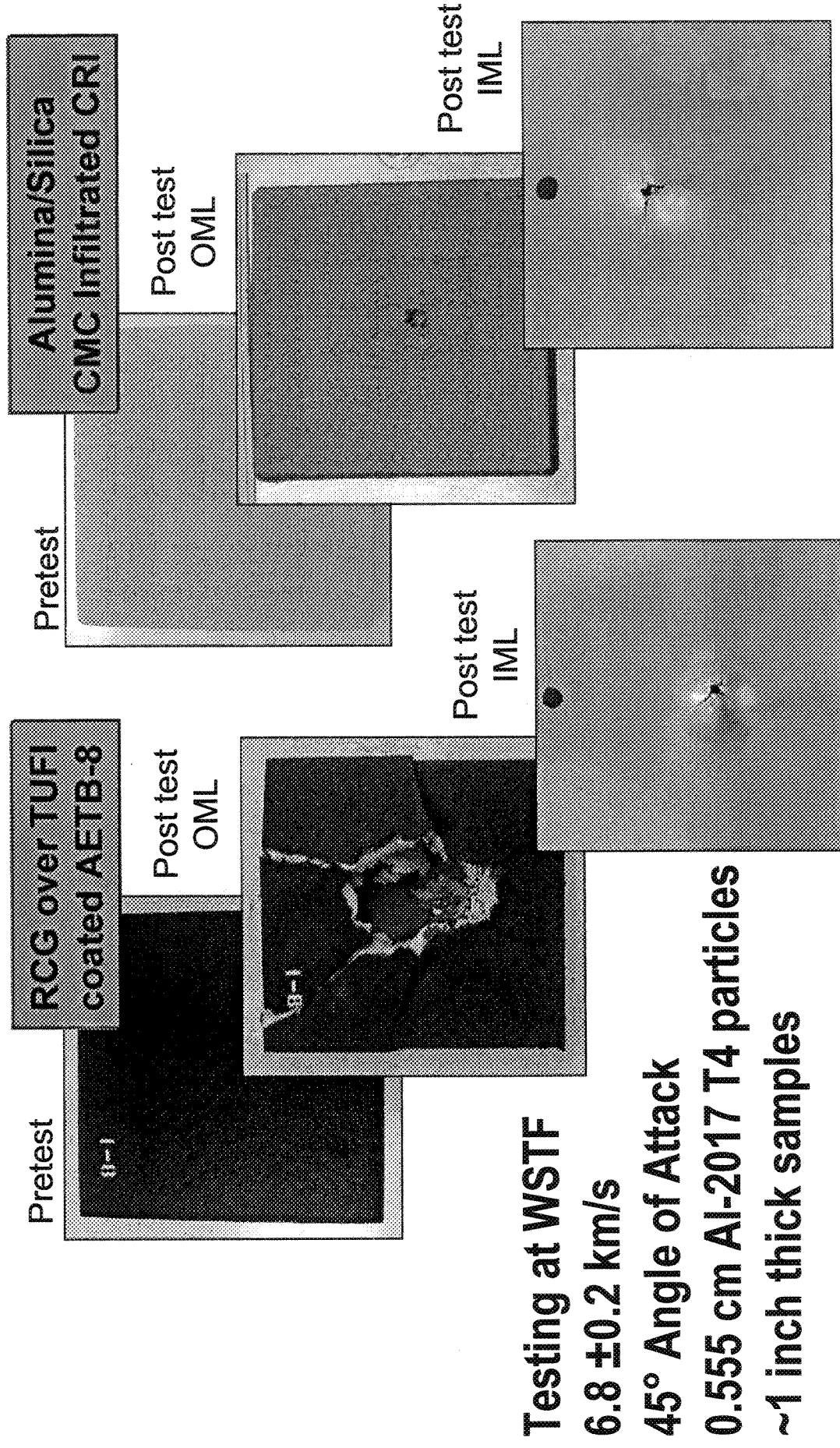


Higher Temperature Flexible

Reusable Surface Insulation (HTFRSI)

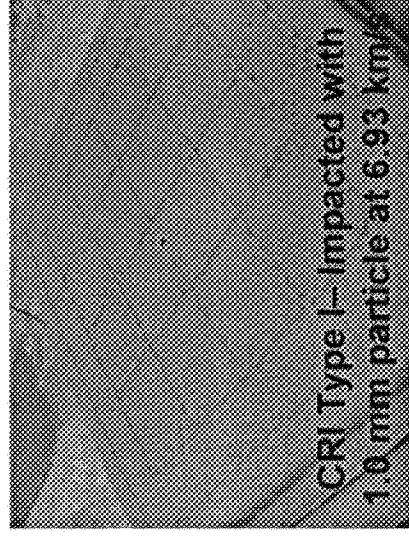
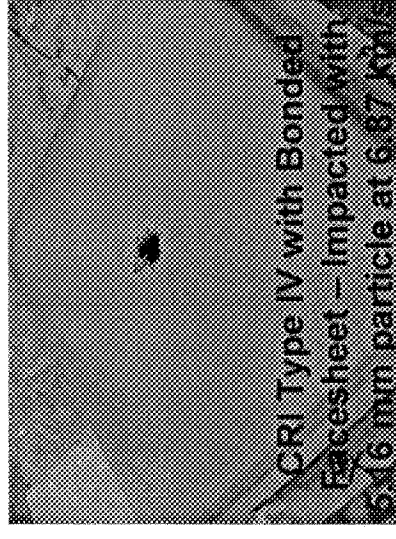
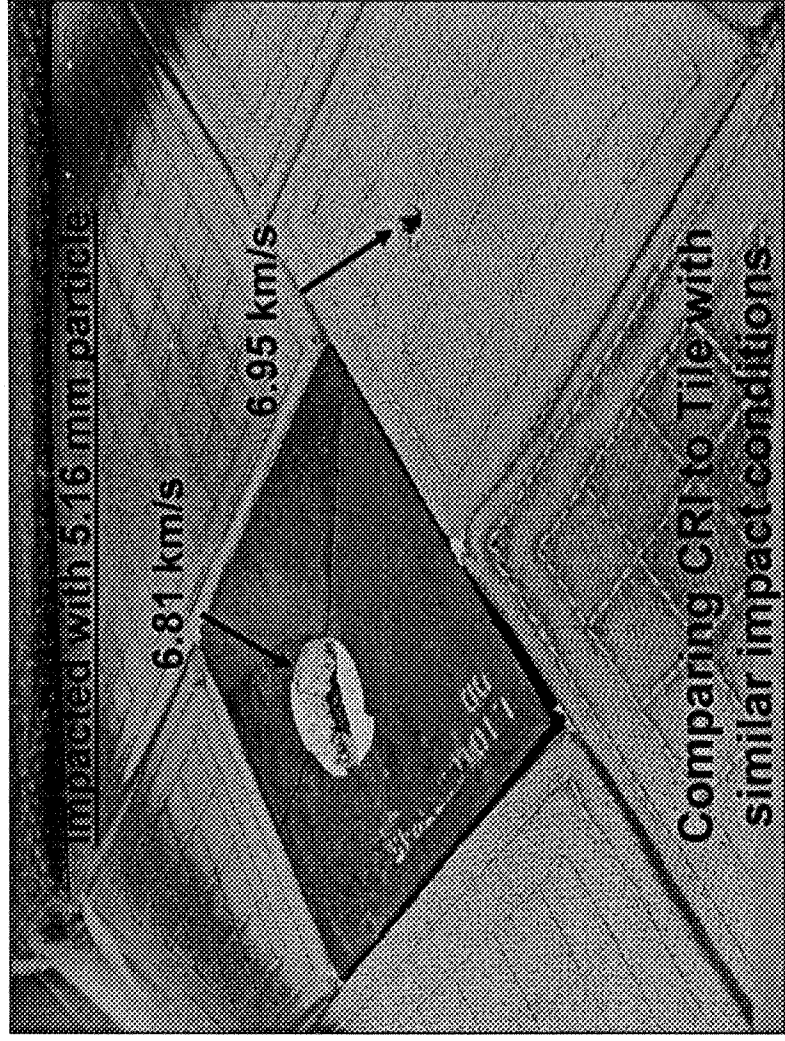
- Durable, Low Cost Acreage TPS applicable to surfaces where $T_{\max} < 900^{\circ}\text{F}$
- Higher Temperature fibrous polymer Felt TPS based on heritage nomex FRSI

CRI Performs Similarly to Tough Tile in Hypervelocity Testing



Verified CRI Is Stable During Reentry Heating After Hypervelocity Particle Impacts

Multiple CRI blankets were impacted with hypervelocity particles to simulate various on-orbit damages. These samples were then tested in an arc-jet to evaluate survivability & thermal performance during a single reentry heating cycle.



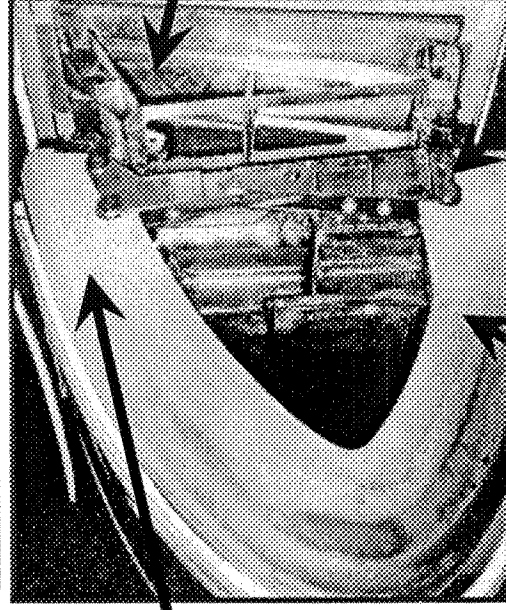
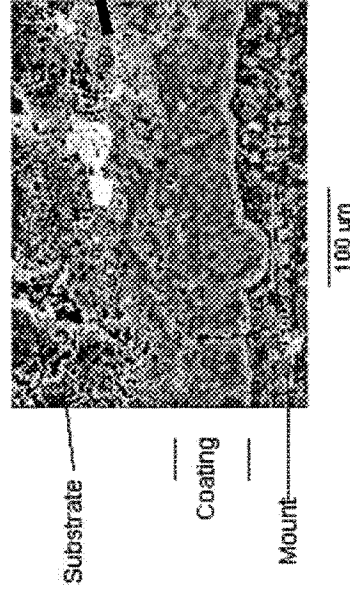
All tests were successful showing no loss of material or excessive thermal heating to the substructure.

3000°F Passive Leading Edges

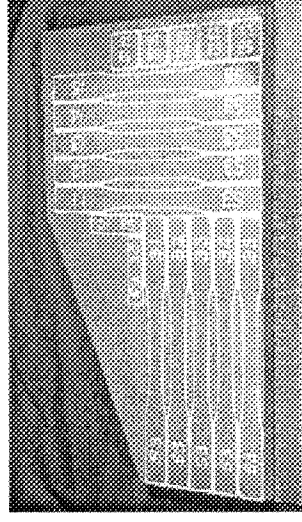
♦ Objective

- Provide a C/C material system (substrate and coating) for lightly loaded leading edges with a multi-use temperature of ~ 3000°F

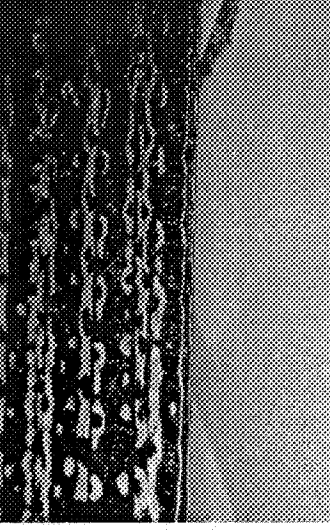
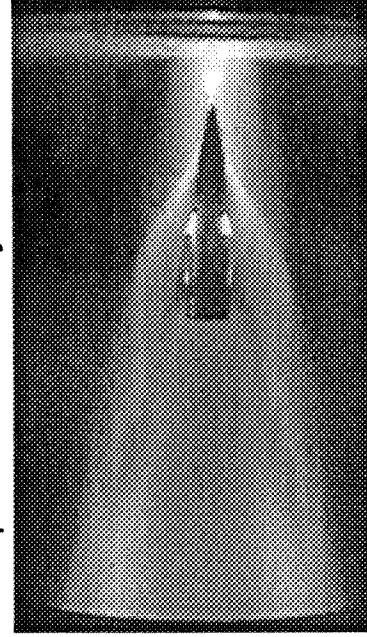
- ♦ Explore CTE mismatch between coating and substrate via an analytical study, use of hybrid fiber architecture, and functionally graded matrix



- ♦ Investigate rapid processing and non CVD coating techniques



- ♦ Investigate coating and sealant chemistries for higher temperature durability



- ♦ Investigate high and low conductivity fiber systems

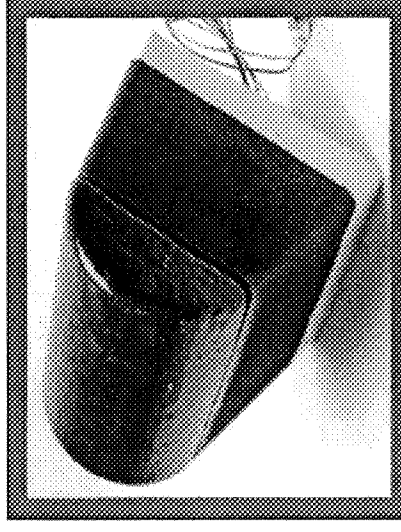
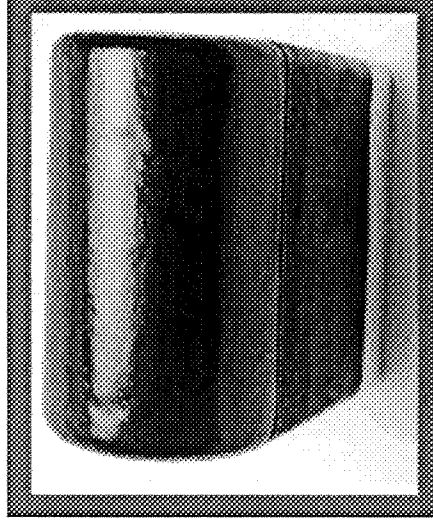
X-37 Wing Leading Edge TPS Accomplishments/Future Work

Completed

- ◆ NASA Ames tested WLE materials 2003
- ◆ Down selected to TUFROC material 2003

Future Work

- ◆ BRI-20 process qualification
- ◆ HETC on BRI-20 process reproducibility at NASA Ames
- ◆ Nose cap arc jet testing at Ames
- ◆ 10x10x6 inch BRI-20 arc-jet test article production
- ◆ WLE Swept configuration arc jet test at NASA Ames
- ◆ ROCCI process reproducibility at NASA Ames
- ◆ HETC on ROCCI process reproducibility at NASA Ames
- ◆ Process reproducibility of TUFROC System
- ◆ WLE component part Certification and arc jet test
- ◆ WLE TPS qualification and certification complete



3600°F Passive Leading Edges

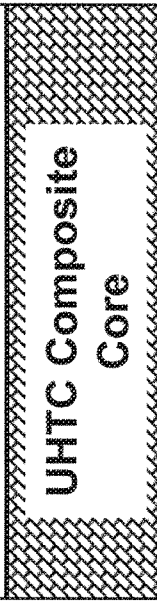
NEXT GENERATION LAUNCH TECHNOLOGY

◆ **Objective**

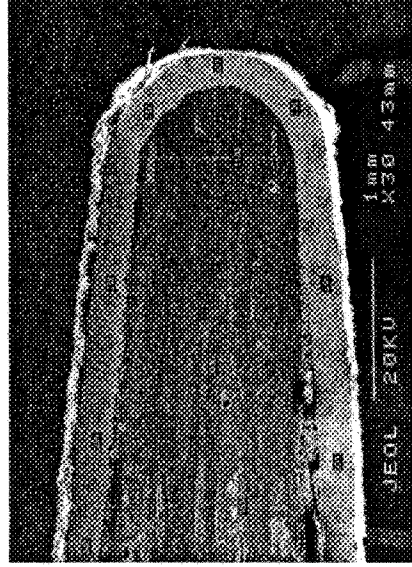
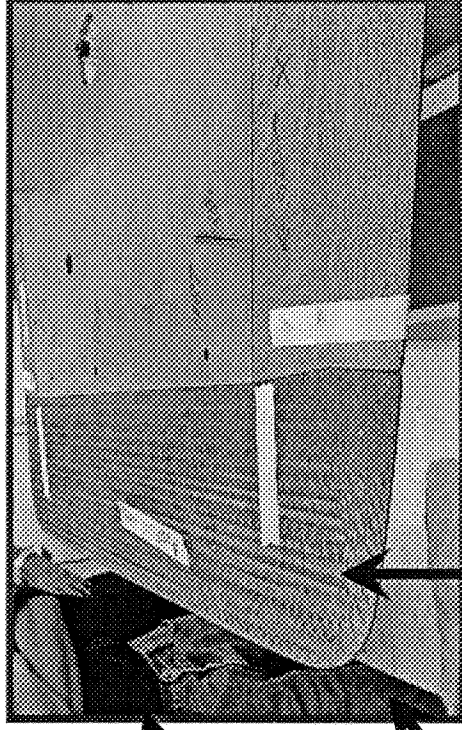
- Develop a composite material system (substrate and coating) for lightly loaded leading edges with a multi-use temperature > 3600°F

Oxidation Resistant Coating

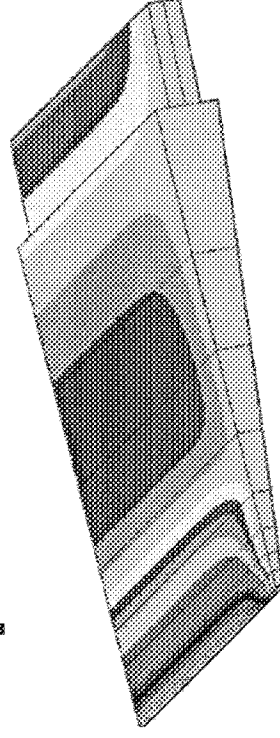
Functionally Graded Transition



- ◆ Develop carbon fiber reinforce ceramic matrix composites and coatings



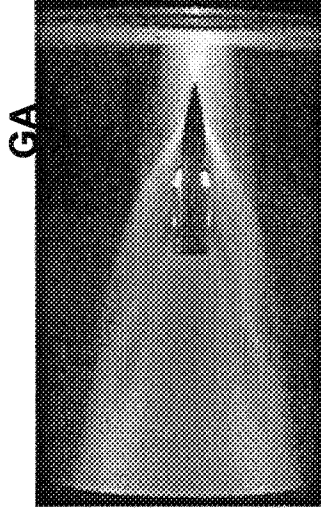
- ◆ Develop coatings for C/C.



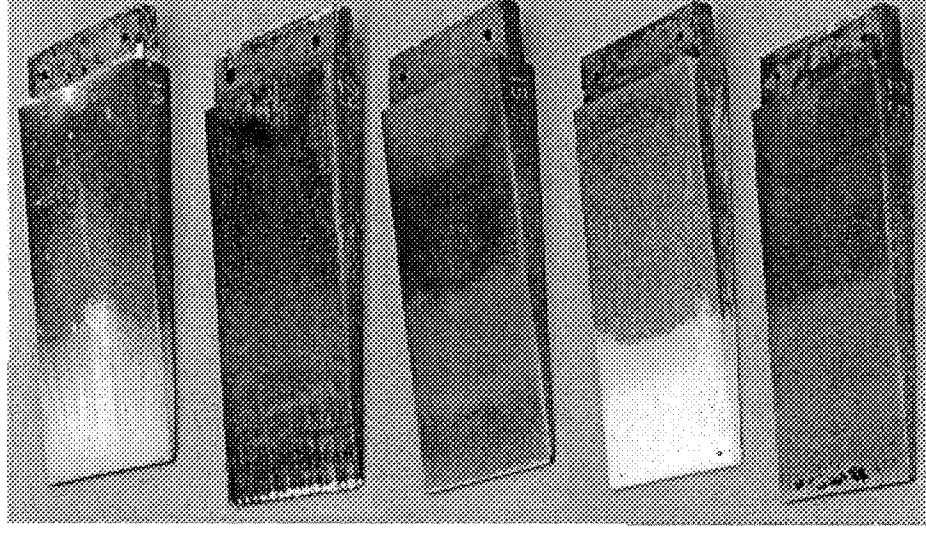
- ◆ Develop and verify analytic tools for design and analysis of C/C fiber architectures for leading-edge applications.

X-43 Mach 10 Leading Edge and Coating Testing

- Flight conditions simulated during AEDC arc-jet test
 - Mach 10, 105,000 ft
 - Enthalpy = 2000 Btu/lb
 - $P_{t2} = 1.15$ atm
 - $q_{\text{cold wall}} \sim 1300$ Btu/ft²-s
 - 130 sec
- Each survived all tests
- Several use BFG K321 5:1 C/C substrate



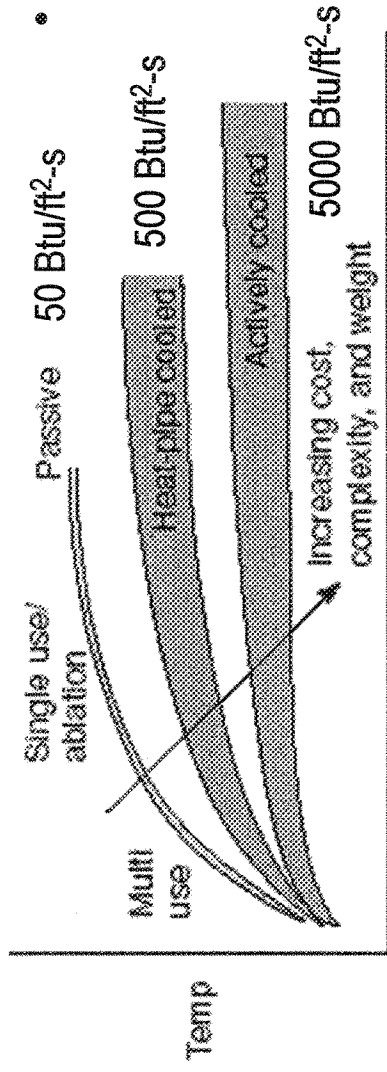
Photograph during test



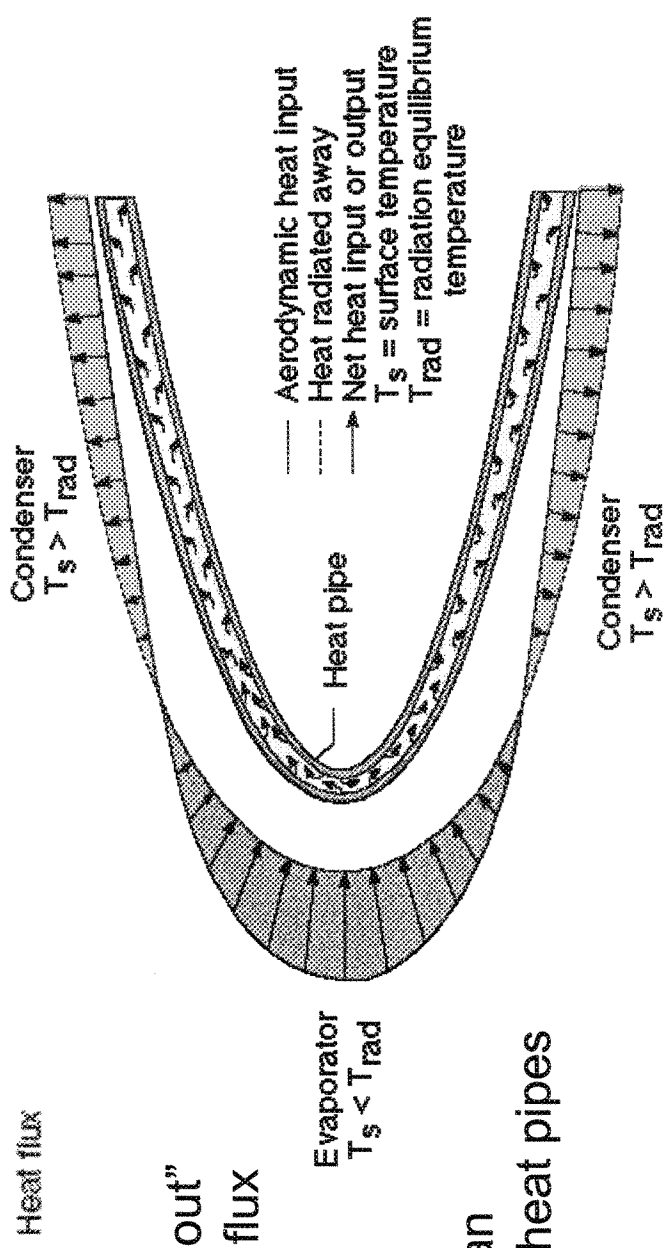
Post-test photographs

<u>Coating</u>	<u>Vendor</u>
Ir/HfO ₂	(Engelhard)
HfC-based	(RCI)
Si ₃ N ₄	(Synterials)
HfC/HfB ₂	(GA)
SiC/HfC	(MER)

Heat-Pipe-Cooled Leading Edges



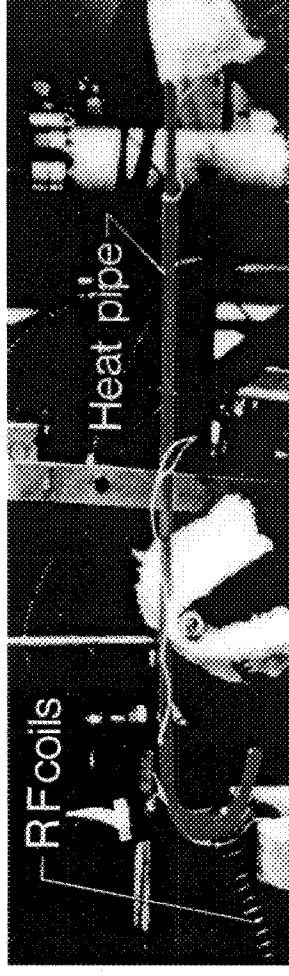
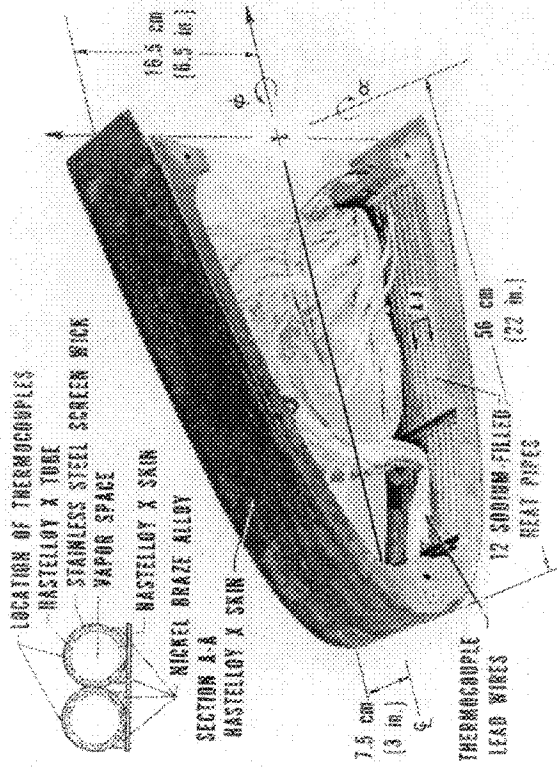
- Heat pipes offer a light weight option for intermediate heat fluxes



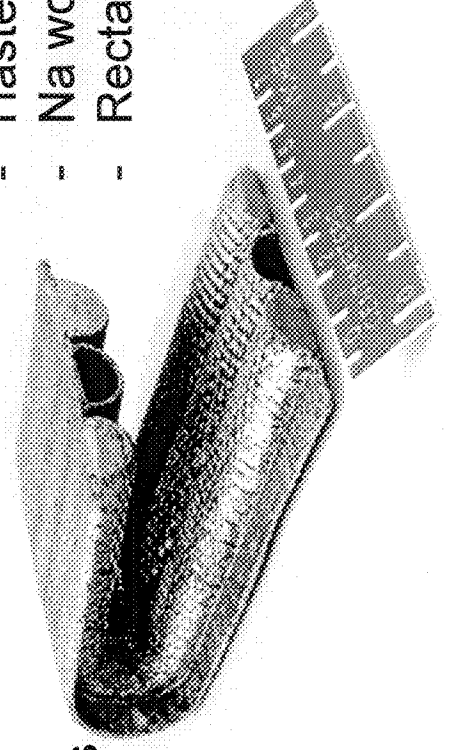
- Heat pipes “smooth out” regions of high heat flux
- Leading edges are an ideal application for heat pipes

Heat-Pipe Wing Leading-Edge Test Articles

- Shuttle - heavy
 - Hastelloy-X container/wick
 - Na working fluid
 - Circular heat pipes

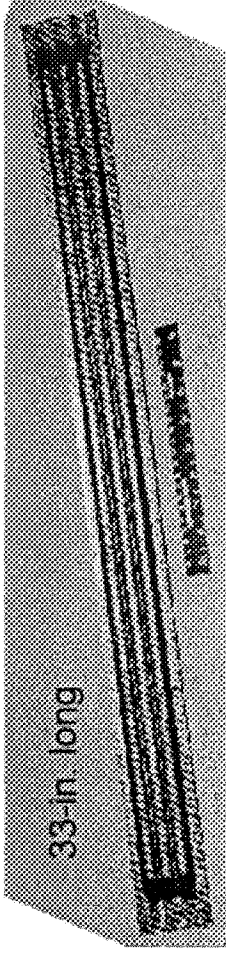


- Advanced STS
 - Hastelloy-X container/wick
 - Na working fluid
 - Rectangular heat pipes



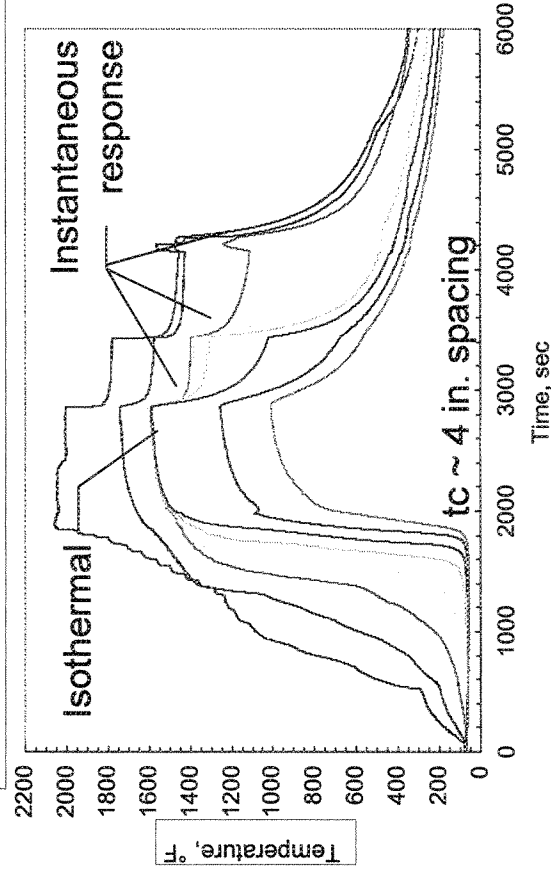
- Advanced systems - significant weight savings (Designed for NASP)
 - Mo-Re container/wick embedded in C/C
 - Li working fluid
 - D-shaped heat pipes

C/C Heat-Pipe-Cooled Component



- Heat-pipe container:
 - 0.010-in. arc cast Mo-41Re
 - High strength
 - High use temperature
 - Ductile at room temperature
 - Weldable
- Heat-pipe working fluid:
 - Lithium
 - Compatible with refractory metals
- Refractory-composite structure:
 - 0.040-in. 3-D C/C or C/SiC
 - High use temperature
 - Lightweight

- Heat pipes maintained “cool” surface with $q_{inc} > 500 \text{ Btu/ft}^2\text{-s}$ (passive surface would have been $> 5500^\circ\text{F}$)



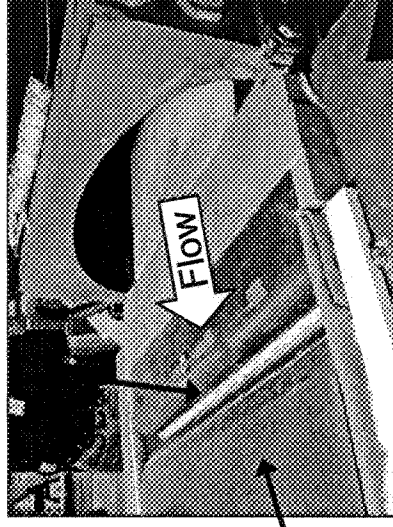
C/C heat-pipe temperature distribution

Control Surface Seals

♦ Objective

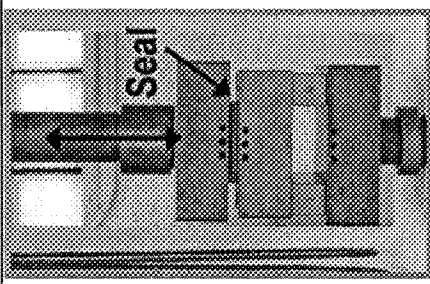
- Develop robust, reusable, high temperature control surface seal concepts and verify performance in simulated environments

♦ Arc jet tests

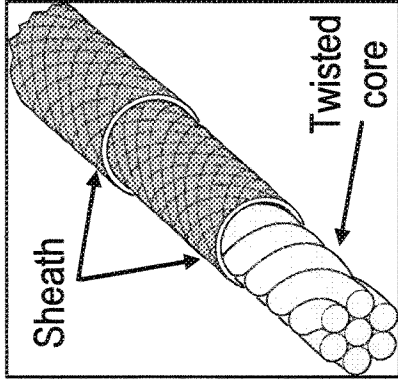


Future CMC body flap

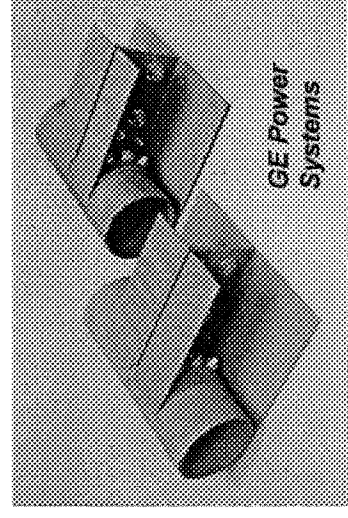
♦ Critical function tests



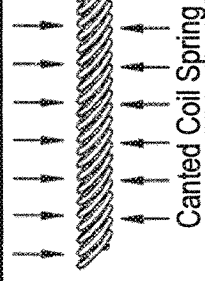
♦ Concept development



♦ CMC control surface seals



Wave spring

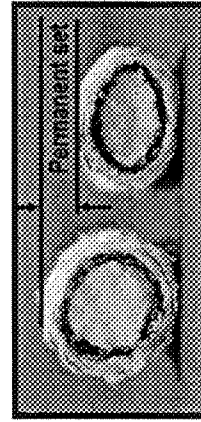


Canted Coil Spring

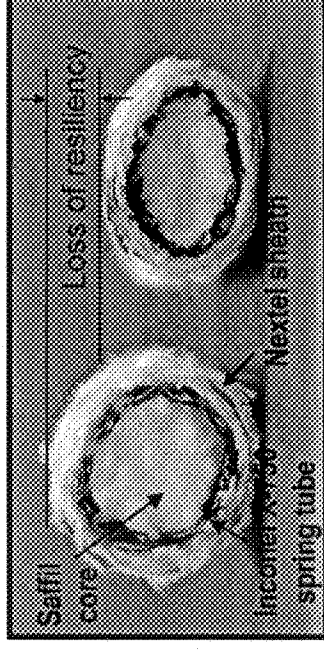
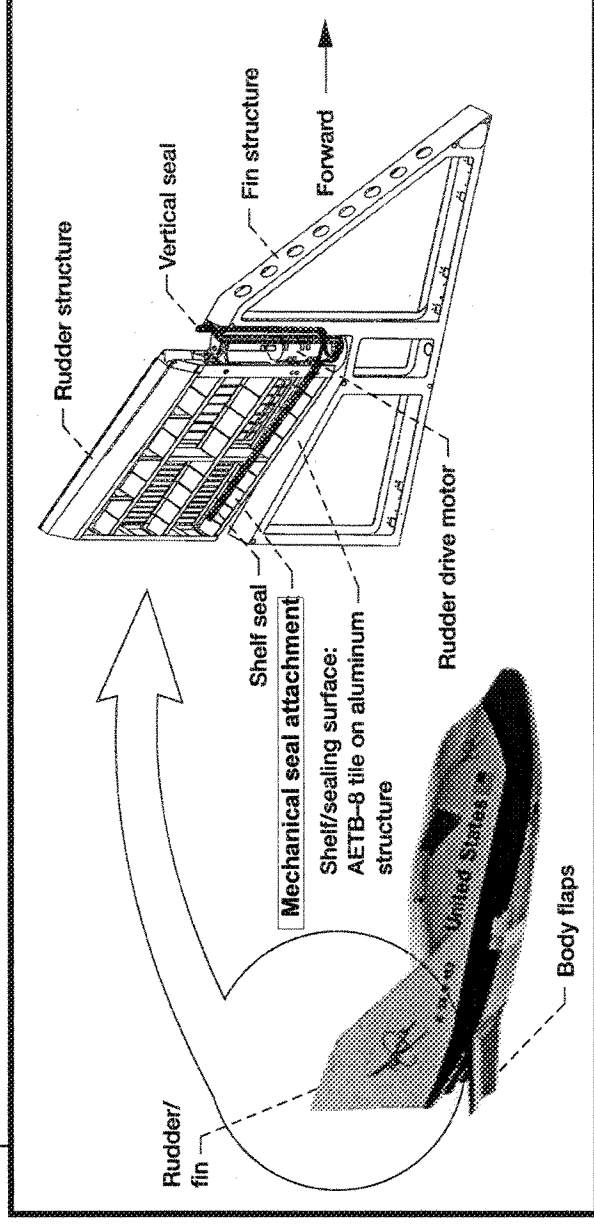
♦ Seal preloader development (e.g. ceramic, refractory metal)

♦ Current seal SOA

Issue: Loss of Resiliency



X-38 Rudder/Fin Control Surface Seals



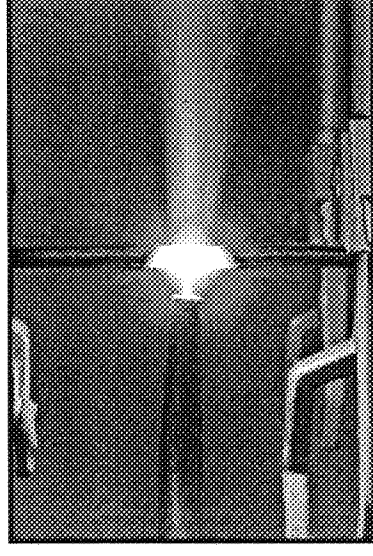
Rudder/fin seal (0.62 in. diam.)

- ◆ X-38 rudder/fin control surface seal drawn from Shuttle thermal barrier technology;
- ◆ GRC/JSC tests showed that seal could only be used for single mission
 - Compression of seal at anticipated 1900°F operating temperature caused loss of resiliency due to permanent set of Inconel X-750 spring tube
 - Loss of seal resiliency required redesign of adjacent sealing surface to prevent gap openings during flight
 - Rough sealing surfaces damaged seals during actuation and scrubbing

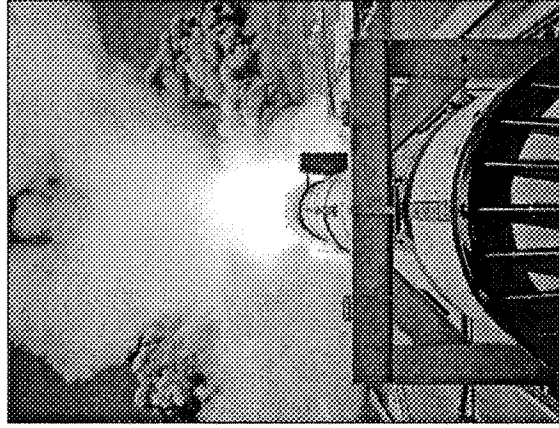
Limitations of existing seal technology led to NGLT support of advanced control surface seal development

Thermal Barrier for Solid Rocket Motor Nozzle Joints

- ◆ Thiokol redesigned Shuttle RSRM nozzle joints with GRC carbon fiber rope (CFR) thermal barrier to prevent hot (5500°F) gas from affecting downstream O-rings. Currently assembling RSRM's with thermal barrier for future flights
- ◆ Based on success in Shuttle RSRM's, Aerojet using three thermal barriers in nozzle-to-case joint of Atlas V SRM's to protect O-rings from hot (5500°F) gases
- ◆ Lockheed-Martin/Aerojet Atlas V incorporating GRC thermal barriers successfully launched July 17, 2003



GRC 5500°F burn test on thermal barrier



Full-scale test of GRC thermal barrier in Shuttle RSRM



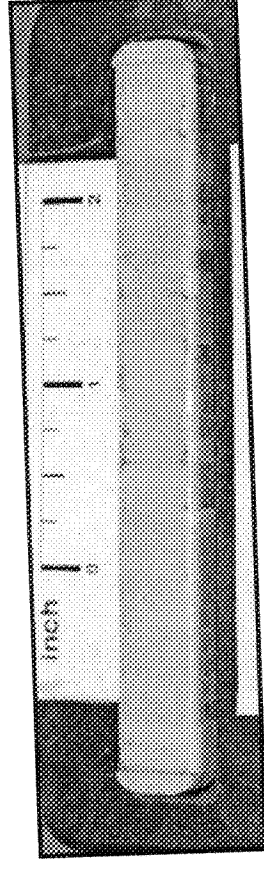
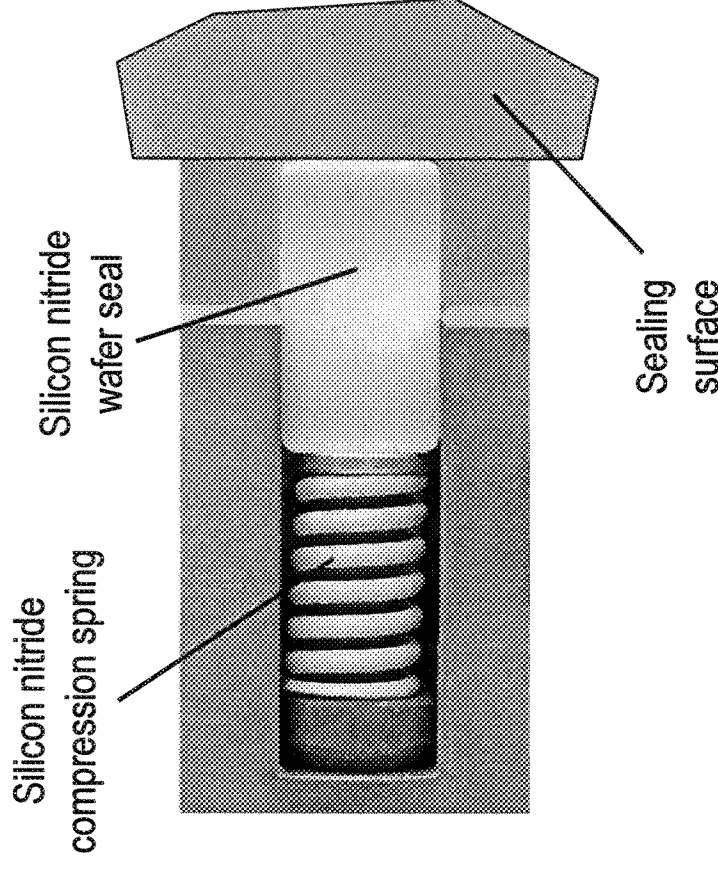
Full-scale test of Atlas V SRM with GRC thermal barriers



Atlas V launch including GRC thermal barriers

Control Surface Seals

- ◆ GRC has developed a unique, high temperature, flexible ceramic wafer seal.
- ◆ Operating temperature limited only to the limit of wafer material
 - Si_3N_4 : 2550°F long term, 3000°F short term
 - SiC: 3000°F long term
- ◆ Silicon nitride wafer seals on top of silicon nitride compression springs show promise as durable, resilient sealing system.
- ◆ Wafer seal flow rates are up to 32 times lower than those for best braided rope seals
- ◆ Preliminary test results: Wafers survived 1000 scrub cycles at 1600°F with no signs of damage. Future scrub tests planned at higher temperatures
- ◆ Silicon nitride compression springs provided resiliency and kept seal in contact with sealing surface at high temperatures



Wafer seals survived 1000 scrub cycles at 1600°F with no damage to seals

ASTP High Temperature Materials Needs

◆ Airframe

- Hot Structures/Control Surfaces
- Tanks
- TPS



◆ Propulsion

- Rotating Components and Seals
- Flowpath Components

High Temp/High Specific Strength Materials

◆ Objective

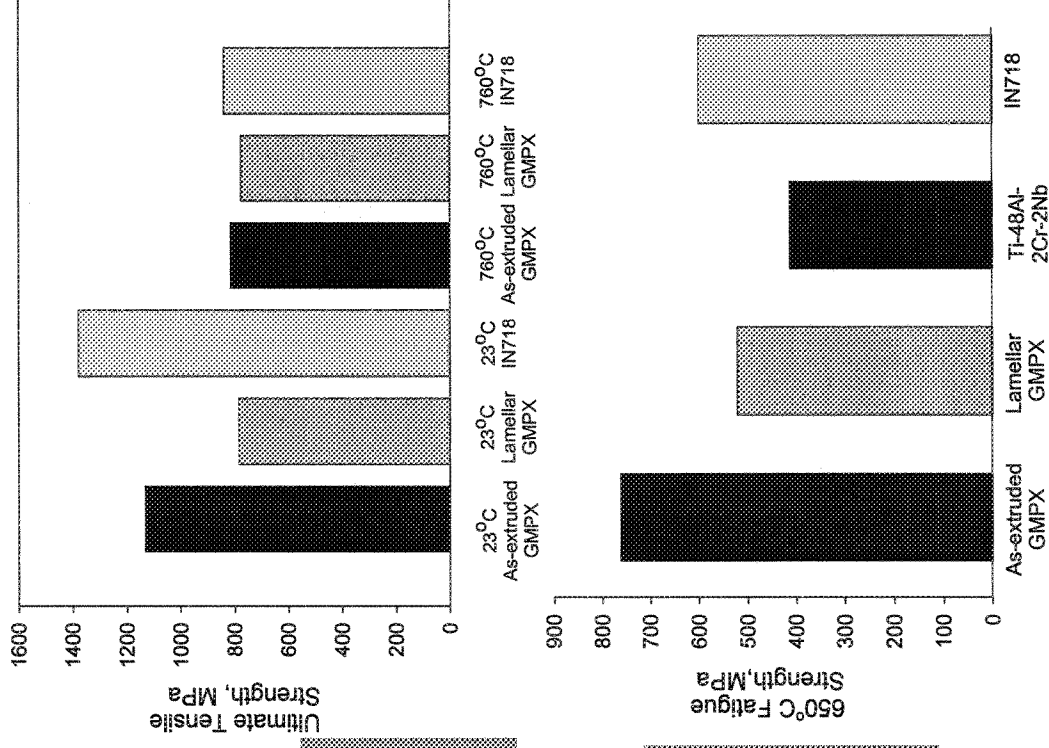
Assess potential of TiAl alloy, Gamma Met PX, for application in RTA as a compressor component and/or potential structural material.

◆ Approach

Determine effect of microstructure and high temperature exposure on mechanical properties of Gamma Met PX.

◆ Benefits

- Reduce weight of compressor components by 30% compared to Ni-base superalloys.
- Reduce weight of backstructure by 40% compared to Ni-base superalloys.



Advanced TiAl Alloy Shown to have Similar Mechanical Properties as Ni-base Superalloys, plus 50% Lower Density

High Temp/High Specific Strength Materials

◆ Objective:

- Achieve weight reduction in TBCC engine through development of turbine blade-to-disk bonding techniques.

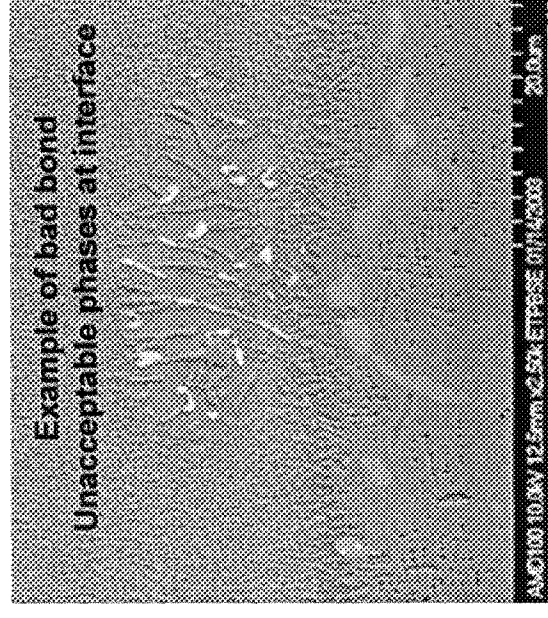
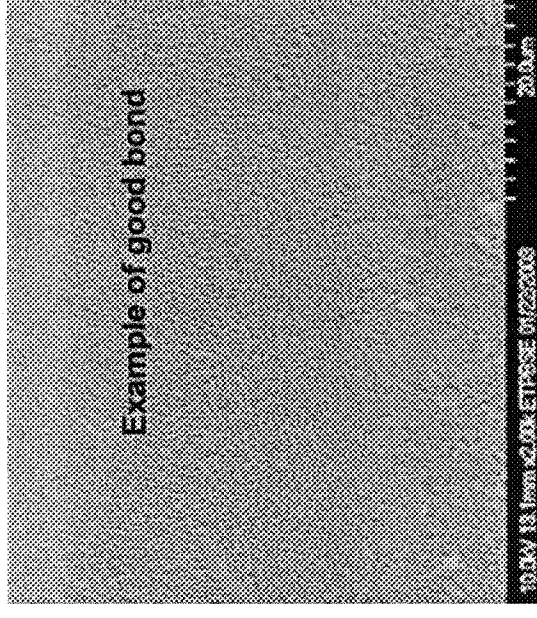
◆ Approach:

- Bond state-of-art single crystal turbine blades to powder metallurgy disk materials.
- Screen candidate braze alloys microstructurally and mechanically.

◆ Accomplishments:

- 17 Ni-base braze alloys evaluated microstructurally after processing and simulated mission testing.
- Several promising braze alloys produced good bonds. Mechanical evaluation to follow.

Bonding of Turbine Blade to Disk Alloys Demonstrated



Actively-Cooled Ceramic Composites

Objective

Develop and demonstrate actively-cooled ceramic matrix composites heat exchanger designs that can meet a range of potential thermal and structural requirements for future reusable launch vehicles.

Approach

Various programs have pursued multiple concepts and materials since NASP:

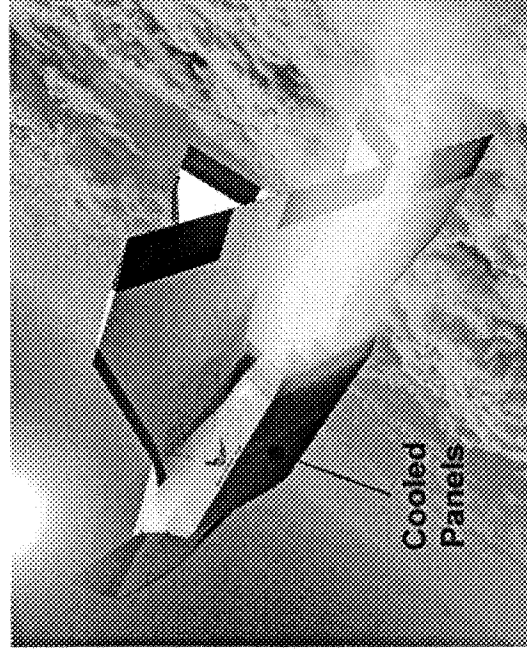
Concepts

- Inserted metal tubes in composite
- Co-processed metallic tubes
- Intimate contact metallic tubes
- All composite heat exchanger

Materials

- Carbon/Carbon (C/C)
- Carbon/Silicon Carbide (C/SiC)
- Silicon Carbide/Silicon Carbide (SiC/SiC)

◆ Current focus is on all-composite systems

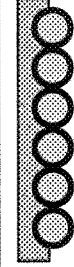


Inserted Metal Tubes in Composite

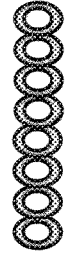
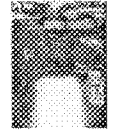
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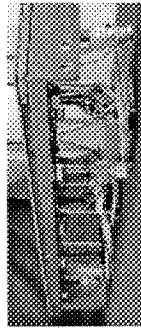
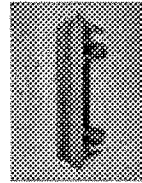
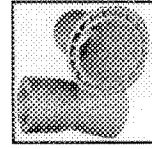
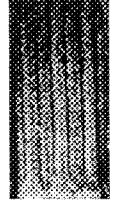
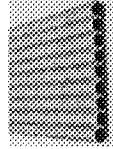
Co-processed Metallic Tubes



Intimate Contact Metallic Tubes

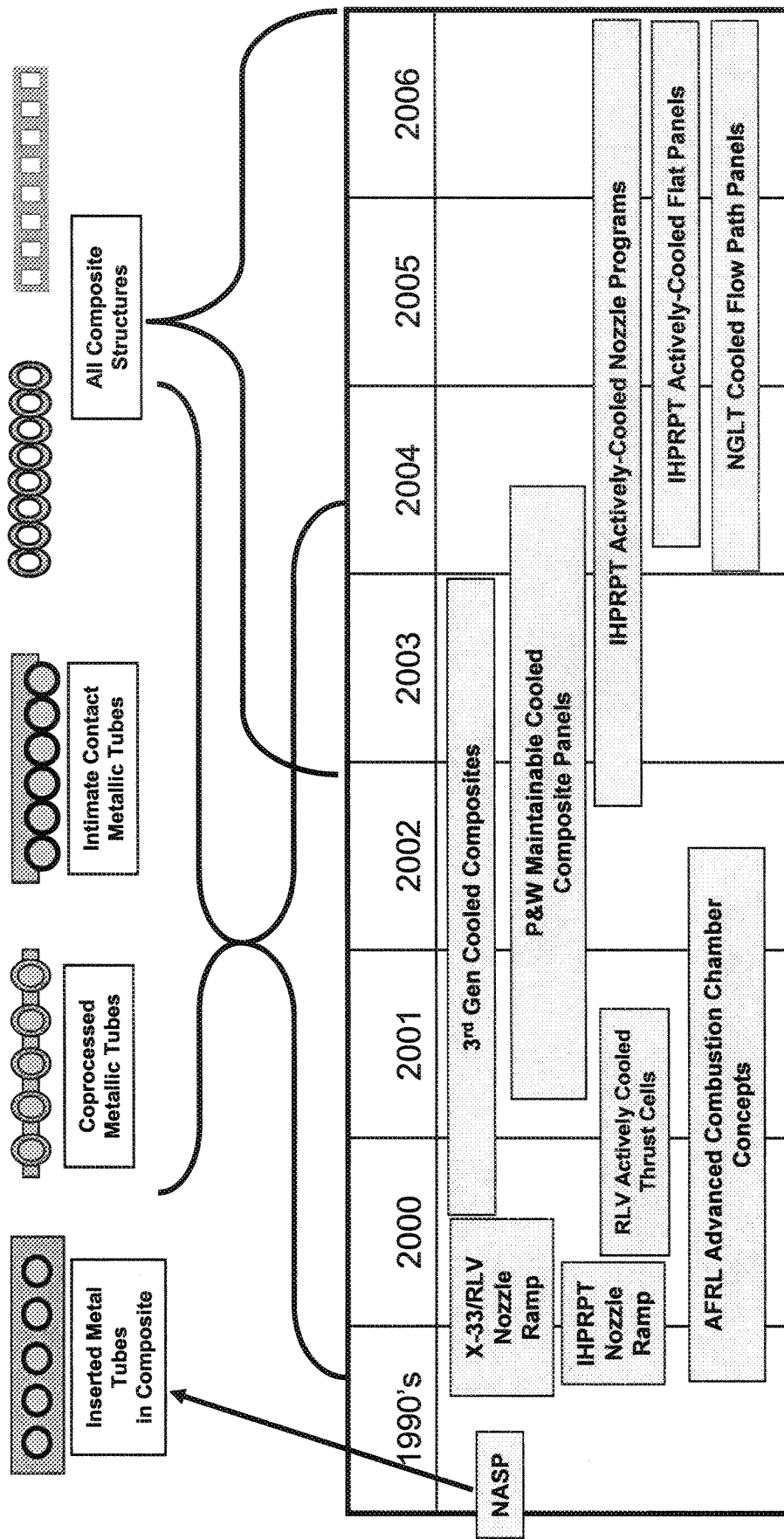


All Composite Structures



6" x 30" Panel

Actively-Cooled Ceramic Composites

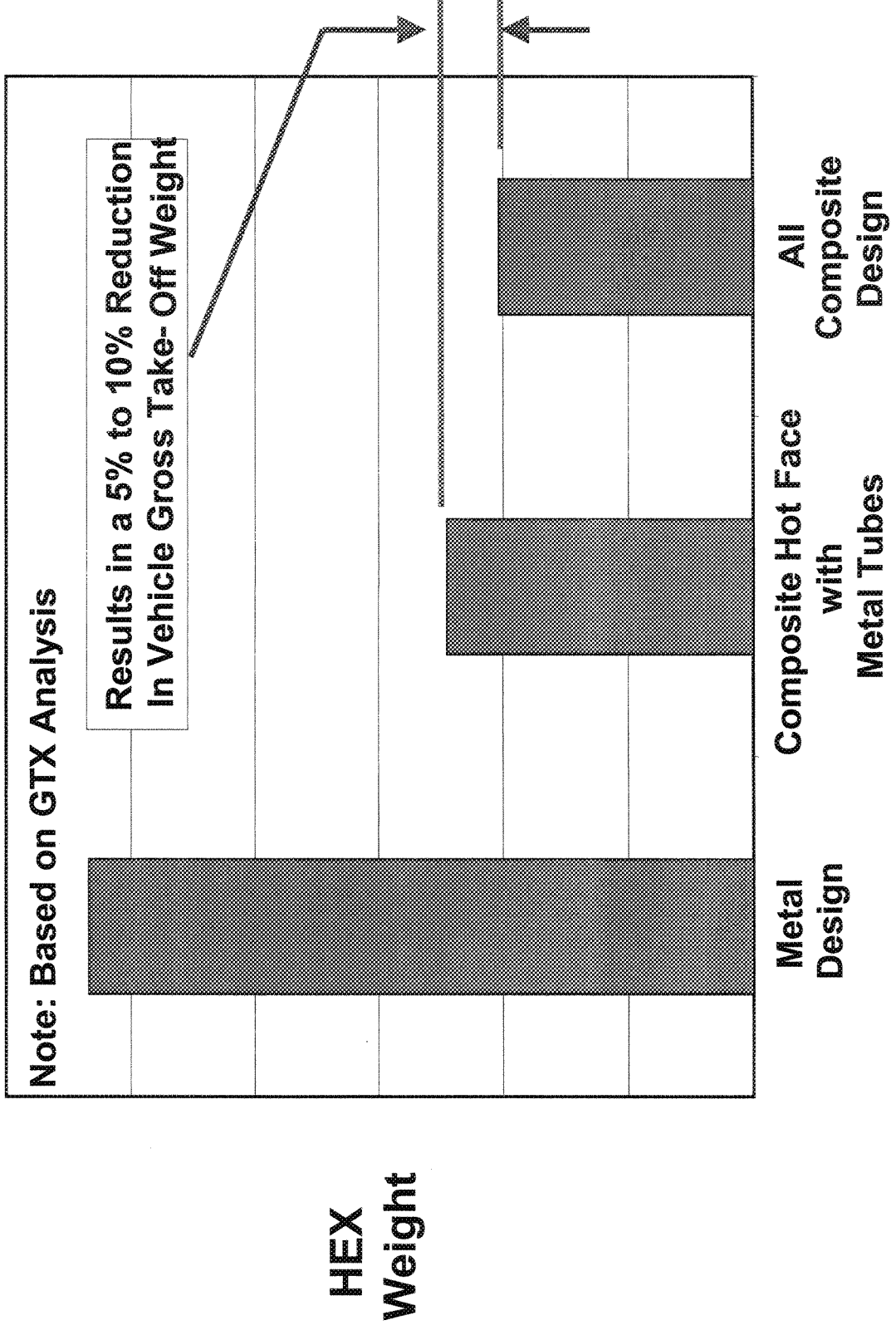


Carbon/Carbon (C/C)

Carbon/Silicon Carbide (C/SiC)

Silicon Carbide/Silicon Carbide (SiC/SiC)

Example of Composite Heat Exchanger Weight Benefits (ref: P&W)



Lightweight High Temperature Structures

◆ Objective:

Develop low melt viscosity polymers for RTM, VARTM or RFI processing of high temperature propulsion components

- Melt viscosities below 20Poise
- T_g and stability suitable for use from 550°F to 750°F

◆ Approach:

Modify oligomer chemistry to reduce viscosity with minimal effect on T_g and stability

- Molecular morphology – branching, twists, asymmetry
- Formulated molecular weight
- Endcap chemistry

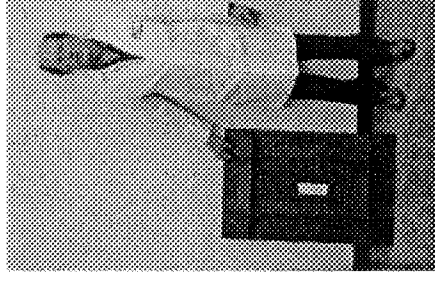
◆ Partners:

Boeing, Clark Atlanta U, Maverick, NASA LaRC, Triton Systems, Tuskegee U

RTM = Resin Transfer Molding
RFI = Resin Film Infusion
VARTM = Vacuum Assisted Resin Transfer Molding



RFI Processed HFPE Panels

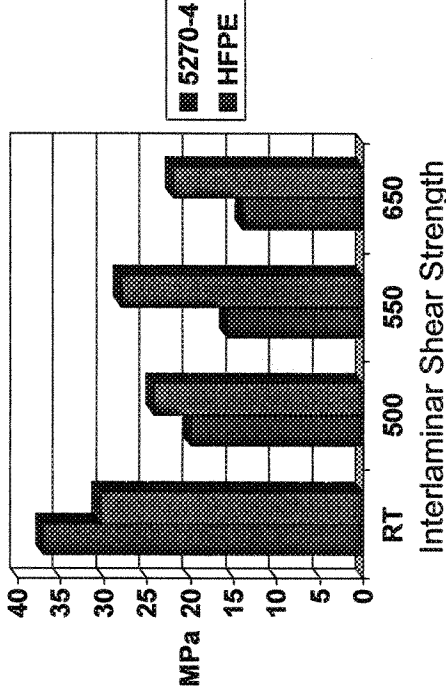


Low Cost Manufacturing
Demonstrated by Boeing

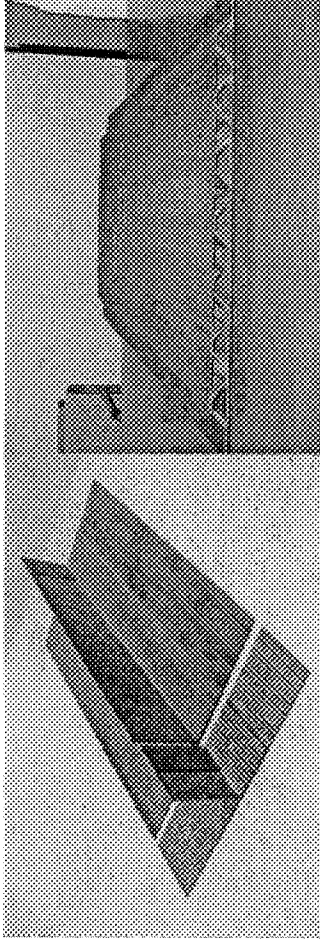
Lightweight High Temperature Structures

GPRA Milestone: Develop RTM processable polymer for use at temperatures up to 550°F (288°C)

67% Retention of RT Properties at 650°F



Complex Structures Made by RFI



Milestone Successfully completed!

New high temperature polyimide, HFPE, developed:

- ✓ Processable by Resin Film Infusion (RTM variant) into a variety of complex shapes
- ✓ Outstanding retention of mechanical properties at temperatures up to 650°F
 - Exceeds milestone target by 100°F and state-of-the-art by 200°F

- Use of HFPE in flow path component backing structures will reduce component weight by 20-30% vs. metallic backing structures
- Further development planned in NGLT
 - ✓ Durability studies with Cornell and Syracuse Universities under Propulsion URETI

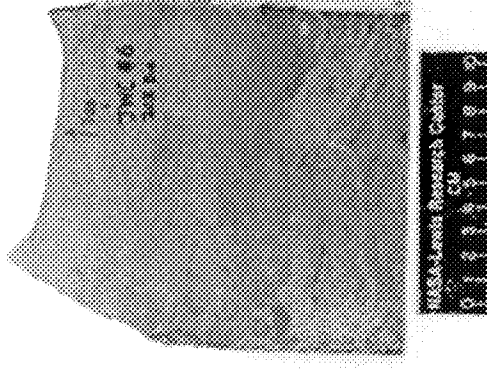
High Conductivity Materials

Objective: Determine feasibility of ultrahigh conductivity metals and composites for high heat flux applications.

- ◆ **Approach:** Examine 3 concepts
 - Cu alloys beyond GRCop-84
 - MMC's made with diamond reinforced copper
 - Nickel Aluminide bimetallics

- ◆ **Benefits:**
 - Higher temperature capability improves rocket performance;
 - Reduces cooling requirements
 - Improves life

- ◆ **Accomplishments:**
 - First ever diamond reinforced copper matrix (D/Cu) metal matrix composites (MMCs) for actively cooled propulsion structures



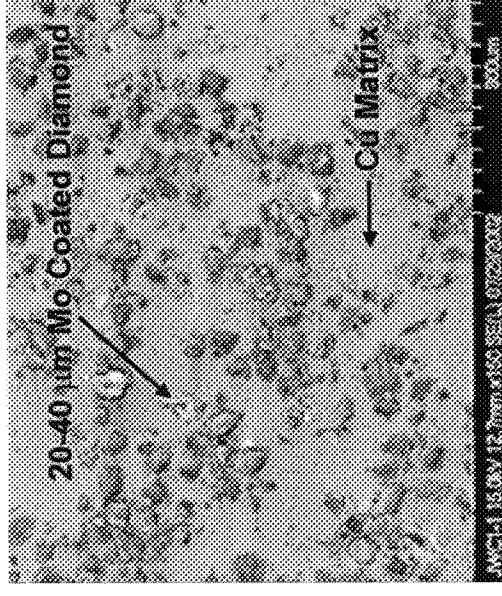
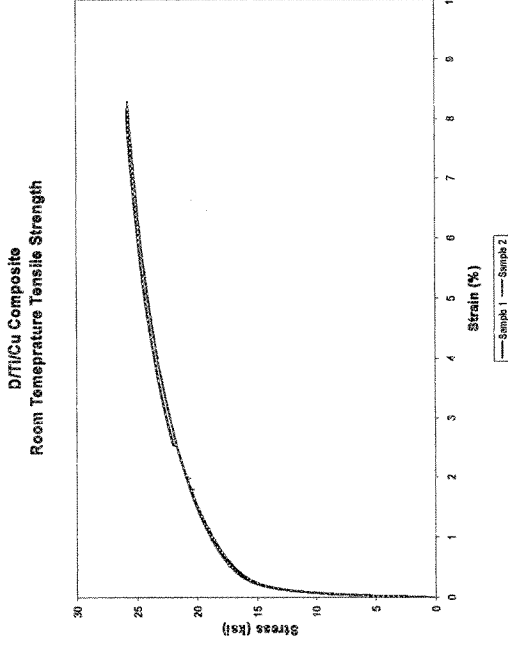
Cast D/Cu Plate

**Diamond/Copper MMCs
Successfully Produced**

High Conductivity Materials

First Ever Particulate Diamond Reinforced Copper Matrix MMCs Tensile Strength Tested

- ◆ Composites show good bonding between copper and diamond particulates
- ◆ Material can be machined using conventional techniques
- ◆ Samples currently being tested for higher thermal conductivity and greater strength than current SOA Cu alloy
 - Properties can be tailored for particular design applications
 - Specimens have fair but not exceptional strength
 - (Yield = 15.5 ksi and UTS = 25.8 ksi
 - Reproducibility & high ductility indicate good consolidation



SEM Micrograph of Cast D/Cu Plate

High Conductivity Materials

◆ Objective:

- Determine feasibility of high-temperature coatings to protect Cu-base materials in aggressive environments

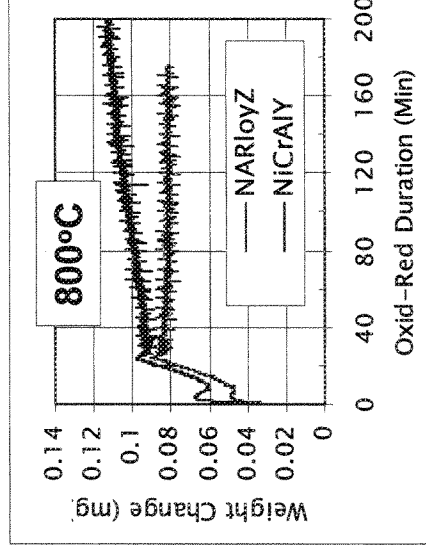
◆ Accomplishments:

- Candidate coatings evaluated in simulated combustion environments
- NiCrAlY confirmed as blanching resistant (in cyclic oxidation-reduction simulations)

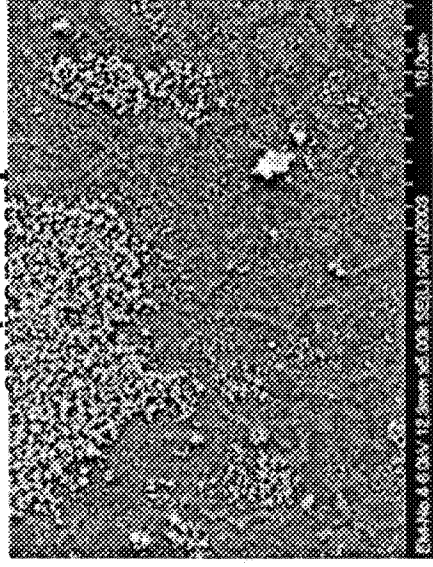
◆ Significance:

- Coatings can extend temperature capability and life of Cu-base materials at lower risk.

Excellent durability of NiCrAlY in combustion environments



Blue curve shows continuous growth of oxide scale, making NiCrAlY resist degradation even in reducing



Summary

- In spite of the current vehicular uncertainty in accomplishing NASA's exploration goals, increasingly higher temperature, lighter weight materials will continue to be key to the success of future NASA missions.
- NASA's current research efforts on high temperature materials are broadly based across material classes (e.g., metallics, polymers, ceramics, composites) but focused on addressing specific issues to enable proposed vehicles.